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1991 BEAUFORT SEA EM/RADAR ICE AND SNOW SOUNDING PROJECT

S.J. Prinsenberg, J.S. Holladay,
J.R. Rossiter, and L.A. Lalumiere

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ABSTRACT

Prinsenberg, S.J., J.S. Holladay, J.R. Rossiter and L.A. Lalumiere, 1992. 1991 Beaufort Sea EM/Radar Ice and Snow Sounding Project. Can. Tech. Rep. Hydrogr. Ocean. Sci. No. 139: vi + 61 pp.

During April 1991, an Electromagnetic (EM) Induction sensor and Impulse (or Ground Penetrating) Radar mounted in an helicopter-towed bird were tested for collection of snow and ice thickness data over the land-fast and mobile ice cover of the Beaufort Sea Shelf. Laser data from the bird's sensor package provided the sensors height above the snow level, the EM data provided the height above the ocean water and the Radar data the height above the snow/ice interface. From this the system can provide in real time the snow and ice thicknesses. Sample data presented in this report show that the system did perform as well as expected for the first test survey with a prototype. Further plans are to use the system off the Newfoundland coast in March 1992 as part of a joint effort between Government Departments to validate SAR ice data of the ERS-1 satellite.

RESUME

Prinsenberg, S.J., J.S. Holladay, J.R. Rossiter and L. A.Lalumiere, 1992. 1991 Beaufort Sea EM/Radar Ice and Snow Sounding Project. Can. Tech. Rep. Hydrogr. Ocean. Sci. No. 139: vi + 61 pp.

En avril 1991, un capteur à induction électromagnétique (EM) et un radar à impulsions (ou géoradar) installés dans une torpille remorquée par hélicoptère ont été mis à l'épreuve pour la collecte de données sur l'épaisseur de la neige et de la glace sur la couverture glacielle de banquise côtière et de banquise de la plate-forme continentale en mer de Beaufort. Les données laser de l'ensemble des capteurs de la torpille indiquaient la hauteur des capteurs par rapport au niveau de la neige; les données EM indiquaient la hauteur au-dessus de l'océan et les données radar la hauteur au-dessus de l'interface neige/glace. À partir de ces données le système fournit en temps réel les épaisseurs de la neige et de la glace. Les échantillons de données présentés dans ce rapport indiquent que le système a fonctionné aussi bien que prévu dans le cadre de ce premier levé expérimental exécuté au moyen d'un prototype. Il est projeté d'utiliser le système au large de la côte de Terre-Neuve en mars 1992 dans le cadre d'un effort mené conjointement par des ministères afin de valider les données RSO sur les glaces du satellite ERS-1.

TABLE CAPTIONS

Table 1. Impulse Radar components.

Table 2. Comparison of EM and on-ice ice+snow thickness data from the transect across the IOS pressure ridge.

Table 3. Airborne and 0n-ice radar data collected during the Beaufort Sea project of April, 1991.

Table 4. Variations in the ice thicknesses and snow depths observed at the calibration site over the two-week survey period. Stations are on a refrozen lead, in a straight line, 50m apart.

FIGURE CAPTIONS

Figure 1. Station locations of Beaufort Shelf sea ice survey of April 1991: station #1, Ice Road (IR); #2, ESSO Site; #3, Shear Ridge (SR); #4, Calibration Site (CS) and 6, 7 and 8 the NRC's ice pressure sites. Stn. #1 is directly east of Tuktoyaktuk.

Figure 2. Sketch of EM/Radar ice and snow thickness data collection system.

Figure 3. Impulse Radar block diagram.

Figure 4. Electromagnetic ice plus snow thickness plots of the IOS pressure ridge.

Figure 5. Raw radar profile data observed while crossing the shear ridge.

Figure 6. On-ice observed snow depth cross-section from the shear ridge (upper panel) compared to processed radar data over the same site (lower panel). Site is shown in Fig. 7.

Figure 7. Sketch of shear ridge site.

1.0 INTRODUCTION

Severe ice conditions over the Grand Banks pose a threat to safe operation of hydrocarbon exploration, marine shipping and fishing activities. Similarly, severe ice thickness and ridge conditions over the Beaufort Sea shelf pose there a threat to safe hydrocarbon exploration. Programs of the Department of Fisheries and Oceans address the seasonal variability, movement of pack ice along the east coast of Canada and the ridge distribution and ridge formation over the Beaufort Sea shelf. Pack ice and ridge thicknesses measured remotely over large areas would greatly benefit these studies.

A practical technique for measuring sea ice thicknesses utilizes electromagnetic (EM) induction and impulse radar sounding from a body towed by a helicopter. This technique is now reaching the end point of its validation stage and is being "hardened" for operational use. The basic method has been demonstrated in the Arctic (Kovacs and Holladay, 1989; Kovacs and Holladay, 1990), and off the Canadian East coast (Maclaren Plansearch, 1988; Holladay et al., 1990; Rossiter et al., 1990). The prototype sensor package being developed for the Canadian Coast Guard underwent initial field testing during April 1991 over land-fast and mobile pack ice off Tuktoyaktuk (NWT) in the Beaufort Sea.

The ice and snow measurement system was a prototype of an operational ice thickness sensor. The design goals of the system were to integrate currently available EM, laser profilometer and radar technology into a package that can be operated by non-expert personnel, installed/dismounted quickly and easily on a variety of helicopters, provide ice thicknesses in real time and make reliable estimates of ice conductivity, and therefore distinguish between first-year and multi-year ice.

This report will summarize the data collected during the Beaufort Sea survey and the future work planned for the EM/Radar system.

2.0 STUDY AREA AND FIELD WORK

The study area covered the land-fast and mobile ice cover over the Beaufort Sea shelf off the coast of the Tuktoyaktuk peninsula in the Northwest Territories (Fig. 1). Facilities of Polar Continental Shelf Project (PCSP) at Tuktoyaktuk were used as the base camp for the survey. All personnel of the ice-sounding survey stayed at the PCSP base camp and used PCSP helicopter support which was provided under contract by Canadian Helicopter Ltd. A Bell 206B helicopter was used to collect on-ice data and a Bell 206L to tow the EM bird. A truck from PCSP was used to collect on-ice Radar data at a site along the ice road from Tuktoyaktuk to Inuvik.

The land-fast ice cover of the Mackenzie delta follows very closely the 10m bottom topography and is separated from the mobile offshore pack ice by a continuous massive shear ridge. Inshore of the shear ridge, the ice cover is relatively smoother than the mobile ice cover offshore. The shear ridge's keel is suspected to be grounded at several places and forms a natural barrier for the low salinity surface runoff of the Mackenzie River (Macdonald and Carmack, 1991). A shallow fresh water layer forms over the saltier oceanic layer; whose deeper water column characteristics were established in the fall and early winter during active ice growth of the land-fast ice cover.

Three stations, #'s 1, 2 and 3 (Fig. 1), were located on the land-fast ice, with station #3, "Shear Ridge", addressing the properties of the shear ridge separating the land-fast ice from the mobile pack ice. Station #1, "Ice Road", was a transect across the ice road between Tuktoyaktuk and Inuvik. Here, the water was shallow (3m). Hard freshwater ice was encountered, with fresh water occurring right to the bottom. Station #2, the "Esso Site", was a grounded man-made ice platform of spray ice containing NRC's ice motion and ice stress instruments. On the mobile pack ice two sites were repeatedly surveyed; the IOS "Pressure Ridge" and a refrozen lead called the "Calibration Site". Farther offshore three multi-year floes had been instrumented by NRC's ice stress panels and were used to test the performance of a new series of Marginal Ice Zone satellite-tracked ice beacons developed by Metocean Ltd. for the Bedford Institute of Oceanography.

The field work covered a 15-day period between April 6 and April 21, 1991. It consisted of three sections; an EM testing period, an EM towing period and an EM/Radar towing period. While the EM system was being readied for helicopter operation (April 6 to 11), a calibration site with uniform ice thickness was established in the offshore pack ice and the radar was tested at the Ice Road site. The calibration site was a refrozen lead, approximately 250m wide and 1000m long and consisted of very uniform 1m thick ice.

While the EM bird was being tested and collected data (April 12 to 17), the radar was towed separately with the 206B helicopter and on-ice data was collected for the "Pressure Ridge" and Shear Ridge" sites. During the last period of 18 to 22 April, the combined sensor package EM/Radar was flown over the three major sites; the calibration site, the pressure ridge and the shear ridge. In addition, more on-ice data was collected to verify results. The day-by-day field work is listed below.

April 5, 1991 - L. Lalumiere and S. Prinsenberg arrived in evening

April 6, 1991 - Arranged for working space and use of truck
Saturday, -25 °C - Unpacked and followed up on equipment shipping

April 7, 1991 - Selected Radar test site along ice road
Sunday, -25 °C - Marked test site (IR), measured snow depths along transect
- Unpacked M. Sayed's augers and Canpolar's Radar equipment

April 8, 1991 - Ice profile at Ice Road (IR), froze in auger
Monday, -29 °C - Elected EM calibration site (CS), 45 miles due North
- Marked and obtained ice thicknesses from EM Cal. site
- Ice profile from EM Cal. Site CS#8
- S. Holladay, V. Schoeggl and I. St John arrived (Evening)

April 9, 1991 - EM Calibration Site line extended, ice profile CS#1
Tuesday, -25 °C - Ice Station IS#2 and Shear ridge station SR#11
- Ice Road Ice thicknesses
- 206B Ice road radar flight in evening
- IOS crew arrived

April 10, 1991 - Unpacked EM Shipment, install computer in helicopter
Wednesday, -20 °C - EM bird readied and ground tested
- Finish Ice Road ice thicknesses
- Ice profile at Ice road IR#7, bottom at 325m

April 11, 1991 - Radar ground truth data from Ice Road snow line
Thursday, -20 °C - Radar data from Ice Road itself
- EM Bird ready in evening

April 12, 1991 - Weather down, salinity samples retested
Friday, -25 °C - Helicopter passed safety equipment test to fly bird
- 206L EM flight Cal Site/ Ice Road/
- 206B Cal Site Ice profile CS#7, Ice Stations #5 and #6
- Radar ground test data from Cal site CS#6-CS#7
- Shear ridge GPS Tracking, marking, ice thicknesses

April 13, 1991 - Weather down in morning
Saturday, -10 °C - 206L EM flight Cal Site
- 206B, Mark and sample snow depths at IOS Pressure Ridge
- Ice Profile IOS Pressure Ridge (PR), Ice Station #7

April 14, 1991 - Extra bags at ends of Cal. Site, Ice thicknesses #7 and #8
Sunday, -15 °C - 206L to IOS Pressure Ridge, ice thicknesses
- Ice Profile PR#5 and PR#6.5
- 206L broke down on way home, 206B brought out engineer

April 15, 1991 - Ice thicknesses CS#7 and CS#8
Monday, -18 °C - EM flight Cal Site afternoon
- EM flight Shear Ridge evening
- Shear ridge ice thicknesses/ CTD and ice samples
- J. Rossiter arrived

April 16, 1991 - CTD with Hydrography at shear ridge
Tuesday, -15 °C - Radar flight Esso Site/ Cal Site/Shear ridge
- EM flight Shear Ridge /Esso Site in afternoon
- EM flight IOS ridge/ Cal site evening
-S. Holladay left

April 17, 1991 - 206B snow depths Esso Site
Wednesday, -5 °C - Radar mounted in EM bird, ground and air tested
- Shear ridge snow depths, Sail height

April 18, 1991 - Weather down; Packed Canpolar equipment
Thursday, -2 °C - Radar snow line by PCSP base camp

April 19, 1991 - L. Lalumiere and J. Rossiter left
Friday, -18 °C - Weather down in morning
- EM/ Radar flight over Shear Ridge/ Cal Site in evening
- CHS ice thicknesses and CTD

April 20, 1991 - 206B located IOS Pressure Ridge brought fuel out
Saturday, -20 °C - Sampled ice blocks of ridge
- 206L EM/Radar flight of Pressure Ridge/Cal Site

April 21, 1991 - Snow storm, unpacked EM console from 206L
Sunday, -12 °C - Packed EM Bird for transport
- Packed EM crates
- Evening, Cal Site to redo ice thicknesses, ice profile
- Shear Ridge block size and ice profile
- Melt and do ice salinity samples, pack up bottles

April 22, 1991 - S. Prinsenberg and I. St John left, V. Schoeggl stayed with Hydrography

3.0 INSTRUMENTATION

3.1 Electromagnetic Sensor

The EM induction method typically uses frequencies in the 50 to 50,000 Hz range. A set of transmitter and receiver coils are towed in a bird at about 15 to 30 m above the ice by an helicopter using a 30m towing cable (Fig. 2). The transmitted primary EM field induces eddy currents in nearby conductors (sea water in this case). This generates secondary EM fields which in turn are detected by the receiver. Since sea water is several orders of magnitude more conductive than ice, sea water becomes the dominant conductor in the ice thickness measurements. By measuring the amplitude and phase of the secondary field relative to the primary field, the distance of the bird to the water/ice interface can be determined. The footprint's radius of the EM signal is comparable to the height of the EM sensor (bird) above the ice.

The bird's laser profilometer used to measure the distance from the bird to the snow/air interface, is an Optech G-150. Its footprint has a radius of $<.05$m when flying the sensor at an attitude of 15-20m.

3.2 Bird and helicopter mounted instrumentation

For the Beaufort Sea survey, the EM, laser and Radar were housed in a bird about 0.4m in diameter, 4m long and weighing 125kg. It is towed on a 30m cable below the helicopter at speeds of up to 150kph. Good flying conditions are required with winds below 40 knots. More details on the bird specification are listed in the text of Rossiter et al., 1991, republished in the Appendix D. Data is transmitted by cable to a data acquisition/logging unit mounted inside the helicopter weighing 50kg. A set of bird altitude sensors measuring pitch and roll are mounted inside the bird. All data were sampled at .05 second intervals, processed in real time and displayed in the helicopter. Observed and processed data were recorded for later processing.

Analog recordings were made on a Panasonic AG-7400 S-VHS video recorder. The recorder was mounted in the helicopter and monitored the ice conditions below the bird. Each image was annotated with time, flight and survey line identifiers. Audio channel 1 was used to record the start-of-scan pulse.

Audio channel 2 was used to record the audio frequency radar data signal. The video channel recorded the picture from a downward looking camera, overlain with time and other information for the EM sensor console. The recorder was powered by a 12 V, 10 Ah gell cell battery or by the EM console.

3.3 Impulse Radar

An impulse radar was first tested over the snow and towed by helicopter as a separate unit before being installed in the bird. The impulse radar system contained a timing control unit, transducer, tow cable, an analog tape recorder and digital acquisition system (DAS). Figure 3 shows how the equipment was wired together. Table 1 lists the equipment along with size and weight specifications.

The timing control unit was a GSSI SIR System 7 and sets the position and length of the radar range window. Audio frequency signals returned from the transducer were passed, untouched through the control unit to the tape recorder and DAS. GSSI model 3102DP transducer was used. It operates with a 500 MHz centre frequency and has a pulse length of 3ns. The transducer houses the receiver and transmitter electronics and the antenna elements. Digital recordings were made using a Toshiba T3100SX laptop computer with a Data Translation DT2812 analog-to-digital converter card plugged into its expansion bus. The computer has 25 megabytes of hard disk space available for data collection. The maximum through-put available with the 3100 was 15 kilo samples per second. The computer was powered by an external 12V, 10 Ah gell cell battery using the two on-board batteries as reserve.

4.0 DATA COLLECTION AND DATA SAMPLES

4.1 Electromagnetic data

During the Beaufort Sea survey, the combination of EM/Laser data was collected prior to installation of the Radar on April 17. After April 17, all three sensors were installed in the bird and data was collected for the next 3 days. Data was mainly collected from the three sites shown in Fig. 1: the shear ridge site (SR), where land-fast ice encounters the mobile offshore pack ice; the calibration site (CS), a very uniform refrozen lead; and the IOS Pressure ridge (PR), where other scientific studies were being done.

However, a number of hardware problems were encountered in "new technology" parts of the system, all of which have been corrected since the field work. These included excessive noise and drift, an error in the calibration, and a weak nonlinearity in the receiver preamplifiers. While the former three difficulties could be overcome in straightforward ways, the nonlinearity (an extremely rare problem in such EM equipment) required major efforts for each flight before the data could be adequately corrected for interpretation. The need for data recalibration meant that the results of the real-time ice thickness calculation, though available, were not usable. Even with the correction applied post-survey, the data are not sufficiently accurate for use in ice conductivity estimation. As a result, relatively few profiles of ice thickness, and none of ice conductivity, have been prepared from the survey results to date.

Samples of the EM/Laser data collected from the IOS pressure ridge site on April 16 are shown in Fig.4. The EM ice thickness were obtained using one dimensional inversion technique. The thickness transects in Fig.4 are in a north-south direction crossing perpendicular over the east-west orientated pressure ridge. The time series plots show the sum of ice and snow thicknesses as well as the altitude at which the bird was towed above the ice. The transect line 1 S-N aligns with line along which on-ice data was collected. This consists of snow layer depths and auger hole ice thickness measurements and are listed in Appendix A under the station PR. Transect line 3 S-N is located 200m east of line 1 S-N. The plots of the bird altitude show that the bird was towed over the ridge at a very constant altitude ranging between 10 and 15m. The footprint's radius of the EM signal will similarly be in the 10 to 15m range. The ridge can clearly be identified and was observed by the EM as being 6m in total height with level a 1.9m thick layer of ice and snow to the south and a thinner 1.1m layer of ice and snow to the north of the ridge. The sum of the ice and snow layer thicknesses at auger holes 50m apart are indicated by crosses on the plots and showed also thinner ice/snow cover to the north of the ridge. Comparison of the site specific data is listed in Table 2. Data from the under water ridge sounding project of IOS indicate that the ridge at the EM data line was in the order of two to three times greater then the 6m estimate from the one-dimensional conversion technique. However primarily analysis, with the two-dimensional technique shows that the EM sensor data represents a 14m maximum keel to sail height value, equal to the observed value (see R. Bowen's paper, Appendix E).

It should be mentioned that the profile data were severely affected by the preamplifier nonlinearity problem mentioned earlier, which was exacerbated by flying the system at a very low altitude in an effort to minimize footprint effects. EM/laser data gathered with similar equipment operating properly typically permits estimation of ice thickness over flat ice to the 0.05 m level or better over profiles ranging from one kilometer to tens of kilometers, with bird altitudes ranging from 10m to 30m (Kovacs and Holladay, 1990). Even after extensive correction, the nonlinearity generated errors which typically range up to 40cm, although considerably better results were observed in many cases. The effect shows up most clearly when the bird's altitude varied significantly from the mean altitude of 12 to 13 meters.

4.2 Raw Impulse Radar Data

A helicopter-borne Ground Penetrating Radar (GPR) collected data during several passes over the five sites shown in Fig.1 during the field trials at Tuktoyaktuk, NWT (Table 3). Raw data was stored on both analog and digital media, for later processing into snow layer depth transects. To date, one profile over the shear ridge (SR) has been processed for snow thickness and compared with on-ice collected data.

Figures 5 and 6 show the raw and processed radar data collected at the shear ridge. The on-ice snow calibration data plotted in Fig.6 is listed in Appendix A. As with the comparison of the EM and on-ice thickness data, it should be remembered that the on-ice data is for a point sample whereas the radar data covers a larger footprint due to the wide beam width of the radiated signal. Horizontal inhomogeneity was found to be much larger for snow depths than for ice thicknesses, making snow depth comparison that much more difficult. Also the bird flight path seldom aligns perfectly with the markers on the ice where the on-ice snow data was collected.

The raw radar data plot (Fig. 5), shows a north to south transect approximately 1km long over the shear ridge site (Fig.7). Zero position on the line is centred over the shear ridge. The area from -100m to 0m in line coordinates was flat with very thin snow cover. From -100m to -200m the surface condition was that of a rough (ice pieces of 0.5m to 1.5m) rubble field. From -200m to -400m the surface altered between small, smooth areas

(10m to 20m diameter) and rough, broken-up areas(about 1m size pieces). To the south of the ridge, from0m to 150m, there were three large drifts of snow. The transect crossed a small ridge, centred at 200m. From 220m to 500m, the ice was flat with snow varying from 0m to 0.3m in small drifts.

For the transect over the shear ridge the radar control unit was set to replicate the radar signal at 12.8 scans per second with a window length of 255ns. The A/D board sampling frequency was 15,000Hz and 1024 samples were collected over each scan. With an effective RF sampling interval of 220ps and the time zero position at sample 72, the remaining window length was 223ns. The plot shown in Fig. 5 is of the lower 110ns of the digitized time window. The dark bands running along the top of the profile are ringing noise from the transmit pulse. The surface level varies due to changing helicopter altitude down the length of the transect.

Over areas of the flat ice, a strong echo is returned from the air/ice or snow/ice interfaces. These echoes are seen as continuous dark bands extending over the area of flat ice, especially noticeable between 0m and 100m. Over rough surfaces, such as the rubble field at -100m to -200m, many small echoes are returned resulting in a grey shaded response.

4.3 Processed Impulse Radar Data

The raw radar plot described above was processed for snow thickness. The results are compared with surface measurements in Fig.6. To process the radar data a model was established as a basis for classifying peaks as ice or snow echoes. The model uses the following assumptions:

-radar footprint diameter is approximately equal to antenna height.
-over a smooth flat reflector most energy is returned from a region with a radius less than one tenth antenna height (first Fresnel zone).
-small radar targets (in a rubble field) return echoes with much smaller amplitudes than large flat targets (flat ice).
-the echo from the ice surface (whether covered by snow or not) has the largest amplitude in the trace.
-the echo from the air/snow interface is the largest signal (over random noise levels) that arrives before the ice echo.

To do the peak locating the filtered data has a smoothing difference function applied to it to convert the peaks to zero crossings. The zero crossings are easily located and peak values from the pre-processed data set are stored in the location of the zero crossings. For every trace the maximum peak value is found and its value and location are stored. This peak might correspond to an echo from the top of the ice. The data is searched for the first peak after time-zero over a threshold. If a peak is found its location and value are recorded. The threshold is chosen to be above the RMS noise level.

The peak locations are processed for snow thickness by subtracting the snow peak position from the ice peak position, dividing by the sampling frequency and multiplying by the radar velocity in the snow. No snow thickness determination is made if:

1. the ice echo is too small
2. no snow echo is found
3. ice peak amplitude is smaller than the snow peak amplitude.

Fig. 6 compares the results from the processed radar data and surface measurements. From -300m to -250m, the helicopter flew at an altitude greater than the radar range window. From -20m to -100m, the surface was flat ice with a thin layer of thin snow. The radar snow thickness results results are near zero. The results from the area 10m either side of the 25m, 35m to 75m and 80m to 100m are profiled quite clearly. From 100m to 220m a small ridge was crossed diagonally. The ridge contained many drifts within rough ice. The results from the radar profile show a large drift north of the ridge, no snow thickness over the centre of the ridge and a small drift south of the ridge. From 220m to the end of the line at 500m, the ice surface is flat with small drifts less than 0.3m high. The radar results are zero when snow thickness is less than about .25m.

4.4 Snow and ice data

On-ice data was collected at all five sites and are listed in the Appendix A. Ice thicknesses were obtained through augered ice holes at 50m intervals, whereas snow layer depths were collected at 5m intervals. The

calibration site (CS) was revisited at the completion of the field trials to check on the ice growth rate in the area during the 2 week survey. The 10 stations showed that over 12 days the 1m thick ice of the refrozen lead grew in thickness by 4.5cm while the snow layer if anything decreased in depth by 1.0cm (Table 4). Thicker ice at other locations would have a similar or smaller change in thickness over the period of the survey.

Ice chip samples were collected from several sites to determine the salinity of the ice (Appendix B). Samples were taken from several depths within the ice cover and from the surface water. The ice chips were placed in sealed containers, melted and tested for salinity by a refractometer in the field and several samples were retested back at the Bedford Institute by the Guildline Autosalimometer. Comparison of refractometer determined salinity values versus Autosalinometer values showed very good comparison but with the refractometer reading consistently low by 0.5ppt (Appendix C).

Except for the ice road site (IR), ice salinities fell in the 3 to 10ppt range when ice chip samples were dry (Appendix B). Some of the samples from larger depths were wet and had higher salinity contents (10-15ppt) as some salty sea water was included in the samples. Ice samples from the ice road site indicated that the ice was formed when surface fresh water was present. Fresh water was also found below the ice in April at this shallow (3m) inshore site. The runoff of the Mackenzie River had formed a fresh water layer under the land-fast ice which was blocked by the keel of the shear-ridge (Macdonald and Carmack, 1991). The surface water salinity on the landward side of the shear ridge was in the order of 5 to 7ppt and changed rapidly over a distance of 1km to 27ppt at an offshore site past the shear ridge. The surface water away from the shear ridge was found to be in the order of 32.0ppt. Ice salinities were lower in the air-exposed ice blocks of both the pressure and shear ridges than the surrounding level sea ice. The lower values (1.5 to 6ppt) suggest that salt drained out possibly due to radiation heating.

5.0 CONCLUSION

5.1 Beaufort Sea survey

In spite of the hardware problems encountered at the start of the project, the maiden survey collected a large amount of data that will be used to determine the capability of the system to monitor ice and snow thicknesses over level ice and ice ridges. In the field, processed data showed that ice and snow thicknesses of level ice can be determined to good accuracy; ice ridges could be identified but further data processing and comparison of IOS's ice ridge thickness data and airborne EM/Radar ice ridge data is required to determine to what accuracy ice ridge thicknesses can be obtained with the EM/Radar technique.

5.2 March 1992 ERS-1 Validation

The airborne EM/Radar system will again be used during March, 1992 over the pack ice off the coast of northern Newfoundland. The survey will be part of a larger project to validate the ERS-1 SAR data when the ERS-1 satellite is in its 3-day ice orbit. The EM/Radar and on-ice auger ice thickness data will be collected using two Bell 206L helicopters from Universal Helicopter Ltd. using St. Anthony, Nfld. as a base for operation. Additional SAR and SLAR data will be collected by CCRS (M. Manore) and Can. Ice Centre (T. Carrieres) using fixed-wing aircraft.

5.3 Further data processing

The large amount of snow Radar data collected during the Beaufort Sea project is being analyzed now by Canpolar Inc. under a separate contract. A robust snow thickness inversion algorithm for snow-ice thickness sensor will be developed before in-depth comparison between observed on-ice data and processed radar data will be done.

While further EM data processing with the 1-D inversion technique may yield a few more profiles of useful ice thickness results, it is clear that extensive efforts to interpret all of the remaining data this way cannot be easily justified at this time. Instead, the data of the Beaufort Sea project will be used to test a two-dimensional inversion technique for special data collected along lines perpendicular to one-dimensional ice structures such as ice

ridges. Under a separate contract, Aerodat Ltd. will implement a 2-D inversion technique for the real-time mode of operation of the TDC EM/Radar sensor package. Both the Beaufort Sea and Labrador data of March 1992 will be used to test the technique (preliminary results are shown in Appendix E).

5.4 Further sensor development

The EM/laser sensor package has already been considerably overhauled since the Tuktoyaktuk survey. A number of noise and drift sources have been located and eliminated, and the preamplifiers have been considerably improved to prevent the possibility of a recurrence of the nonlinearity problem. A series of laboratory tests are being carried out and will be followed by flight testing to verify the dynamic performance of the system prior to further survey work over the Labrador Sea in early 1992. The goal of noise levels of less than 0.05m in real-time ice thickness estimates over flat ice should be reached during this survey, and conductivity estimates capable of differentiating between first-year and multi-year ice should also be obtained at this time.

In the longer term, a series of tests are being considered for 1992, including deployment from icebreaker-based helicopters, to assess the performance of the system under operational conditions. Development of data presentation may begin at this time, as well as work on an improved technique for detailing the geometry of ice ridges using the 2-D inversion technique. Funding permitting, a production prototype of the system will then be constructed and delivered to the Canadian Coast Guard for further evaluation: this could occur as early as 1993.

ACKNOWLEDGEMENT

The authors like to thank the personnel of Polar Continental Shelf Project for their help during the stay at PCSP base camp at Tuktoyaktuk. Under the leadership of Claude Brunet and Barry Hough, their continuing support was most beneficial to the success of the survey. The personnel of Canadian Helicopter Ltd. are thanked for their support; not only for being prompt with helicopter support, but also for helping out with the actual field work. The engineers Chris Broadbent and Lane Voll serviced the helicopters in spite of adverse weather conditions; and the pilots Pierrette Paroz and Bill Derksen were a pleasure to fly with. The assistance provided by personnel of the IOS's ice pressure ridge project, the NRC's ridge geometrics project and the CHS's Electromagnetic sounding project, were appreciated.

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REFERENCES

Bowen, R.B., 1992. Field testing of a state of the art airborne remote sensing system on a first year ice ridge. *Proceedings of Conf. Assoc. of Canadian Universities for Northern Studies. In press, 12p.*

Kovacs, A., and Holladay, J.S., 1989. Airborne Sea Ice Thickness Sounding. In: *Proc. Int. Conf.on Port and Ocean Eng. under Arctic Conditions. Lulea Univ. of Techn, 12-16 June, 1989: 1042-1052.*

Kovacs, A., and Holladay, J.S., 1990. Sea-ice thickness measurements using a small airborne Electromagnetic sounding system. *Geophysics 55(10): 1327-1337.*

Holladay, J.S., Rossiter, J.R., and Kovacs, A., 1990. Airborne measurement of sea-ice thickness using Electromagnetic induction sounding. In: *Proc. 9th Int. Conf. of Offshore Mechanics and Arctic Eng., 1990: 309-315.*

Maclaren Plansearch Ltd., 1988. Study the Sea Ice Climate of the Northumberland Strait. *Rep. to Dept. Fish. and Oceans, Bedford Inst. of Ocean., Contract FP950-7-0058/01-OSC.*

MacDonald, R.W., and Carmack E.C., 1991. The role of large-scale under-ice topography in separating estuary and ocean on an Arctic shelf. *Atmosphere-Oceans 29: 37-53.*

Rossiter, J.R., Holladay, J.S., and Lalumiere, L.A., 1990. Validation of airborne sea ice thickness measurement using Electromagnetic Induction during LIMEX'89 (UP-C8-028). *Rep. to Dept. Fish. and Oceans, Bedford Inst. of Ocean., Contract FP953-8-0848/01-OSC.*

Rossiter, J.R., Holladay, J.S., and Prinsenberg, S.J., 1991. Operational airborne sea ice thickness measurement system. *2nd WMO Operational Ice Remote Sensing Workshop, Ottawa, Ontario, September 10-13, 1991, Vol. 1: 167-177.*

Table 1. Impulse Radar Components.

Item (Type)	Size L x W x H(cm)	Mass (kg)
Control Unit GSSI SIR System 7	44 x 18 x 38	11.0
Skin Cable C-CORE	5.7 m long	1.5
Tow Cable GSSI control cable	45 m long	10.0
Transducer GSSI model 3102DP	31 x 36 x 15	4.0
Computer Toshiba T3100SX	32 x 36 x 10	6.5
1 Gell-Cell battery A200 12V-10Ah	15 x 10 x 10	3.5

Table 2. Comparison of EM and on-ice snow+ice thickness data from a transect across the IOS pressure ridge.

FID #	Station #	Obs. thickness (m)	EM thickness (m)	Diff. (m)
131366	55	1.03	0.66	0.37
131416	50	1.04	0.71	0.33
131456	45	2.63	1.47	1.16
131506	40	1.05	1.35	-0.30
131546	35	1.07	1.19	-0.12
131574	33	1.08	1.54	-0.46
131596	30	1.66	2.52	-0.86
----------	25	---------- Ridge Crest ----------		
131686	20	1.84	1.35	0.49
131726	15	1.84	1.71	0.13
131766	10	1.90	1.60	0.30
131806	5	1.84	1.66	0.18
131846	0	2.17	2.15	0.02

Table 3. Airborne and on-ice radar data collected during the Beaufort Sea project of April, 1991.

Date	Site	Number of low level passes over site	Surface data available
April 9/91	along Ice Road	3	no
	across Ice Road	4	yes
	land and lakes	4	no
April 16/91	Ice Road	2	yes
	ESSO site	1	yes
	Shear Ridge	3	yes
April 18/91	PCSP base	2	yes
April 19/91	Shear Ridge	2	yes
	Cal Site	2	yes
April 20/91	Pressure Ridge	2	yes
	Cal Site	2	yes

Table 4. Variations in the ice thicknesses and snow depths observed at the calibration site over the two-week survey period. Stations are on a refrozen lead, in a straight line, 50m apart.

	----------ICE(cm)----------					-----SNOW(cm)-----		
Stn#	Apr08	Apr12	Apr15	Apr20	Diff.	Apr08	Apr20	Diff
8	97	100	102	104	+7	5	4	-1
7	110	114	106	111	+1	3	3	0
6	100	-	-	95	-5	7	6	-1
5	98	-	-	104	+6	4	6	+2
4	98	-	-	104	+6	5	1	-4
3	100	-	-	104	+4	6	4	-2
2	99	-	-	104	+5	4	3	-1
1	100	-	-	104	+4	4	2	-2
-1*	100	-	-	104	+4	4	5	+1
-2*	100	-	-	109	+9	4	2	-2
MEAN	100			104	+4.5	4.5	3.5	-1.0

* Stations occupied on April 9.

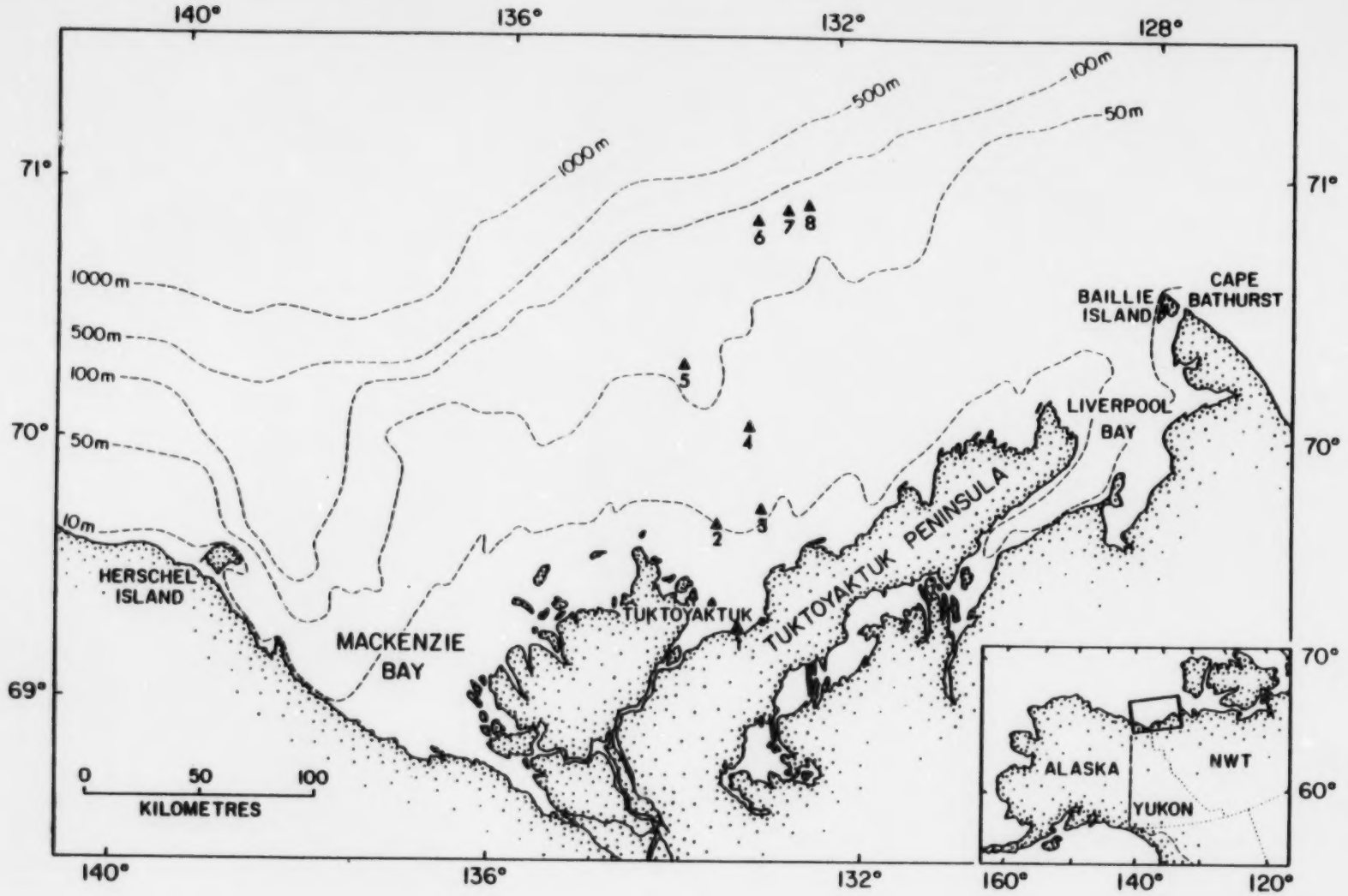

Figure 1. Station locations of Beaufort Shelf sea ice survey of April 1991: station #1, Ice Road (IR); 2#, ESSO Site; #3, Shear Ridge (SR); #4, Calibration Site (CS); #5, Pressure Ridge Site (PR) and 6, 7 and 8 the NRC's ice pressure sites. Stn. #1 is directly east of Tuktoyaktuk.

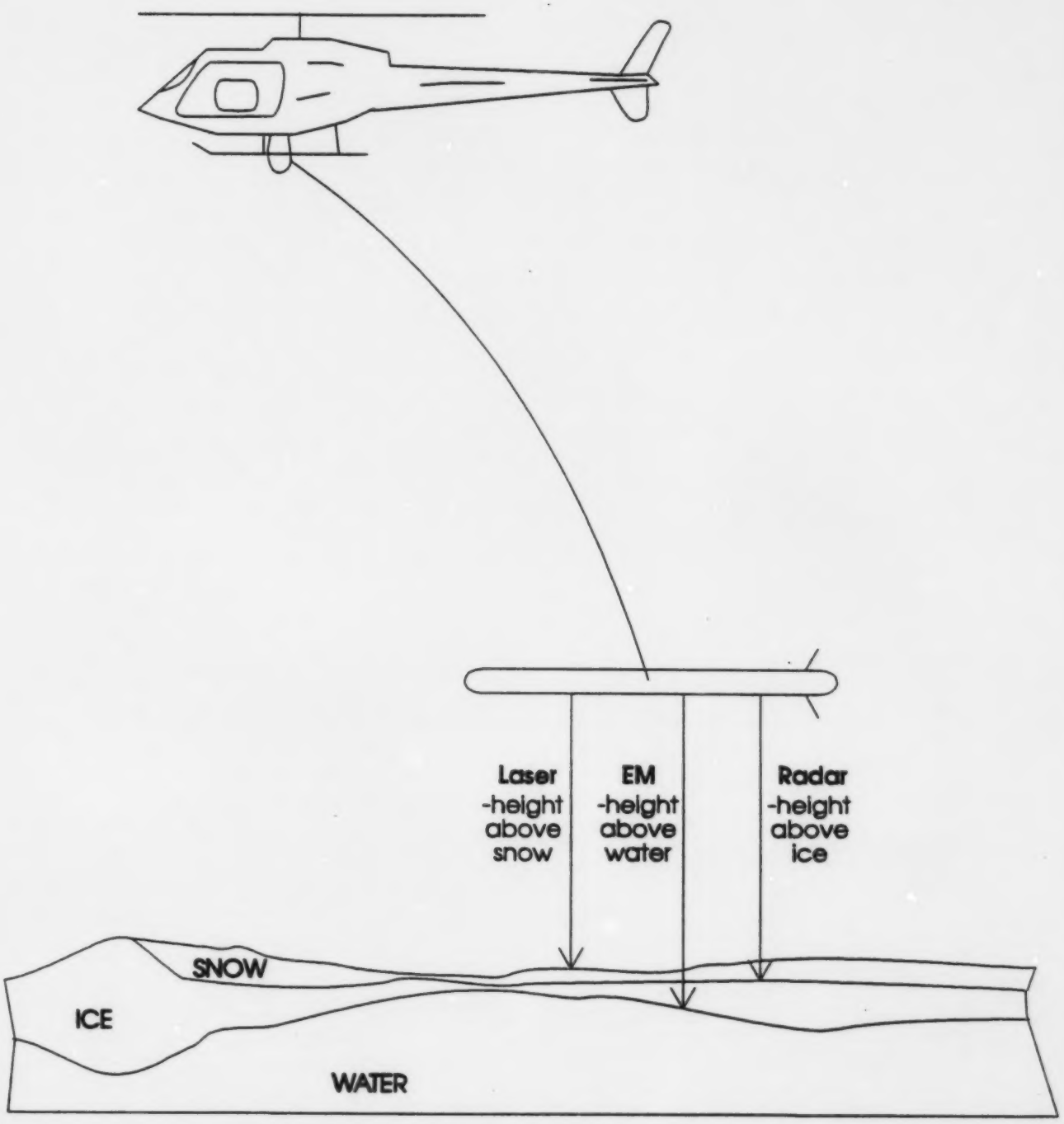

Figure 2. Sketch of EM/Radar ice and snow thickness data collection system.

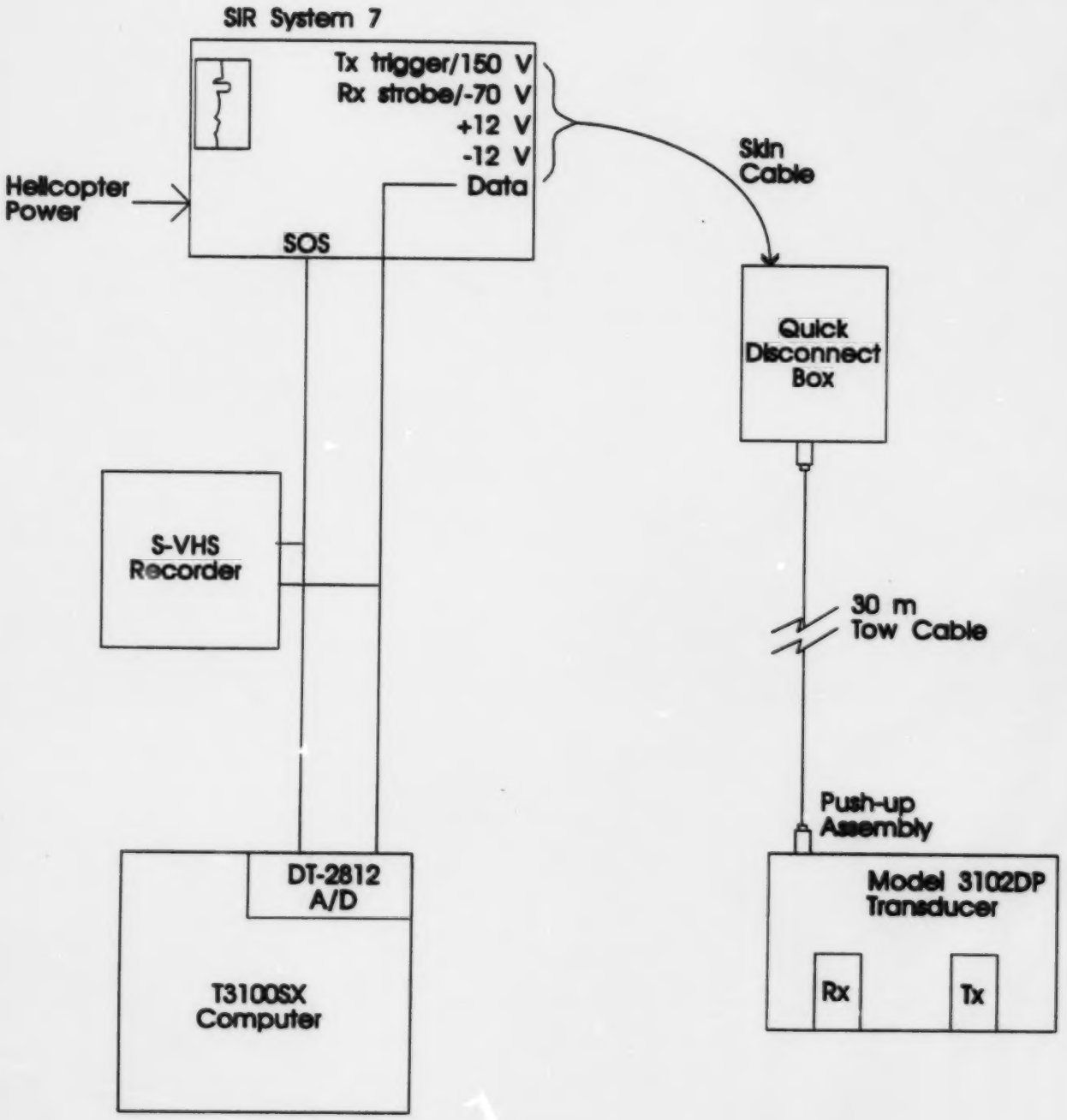

Figure 3. Impulse Radar block diagram.

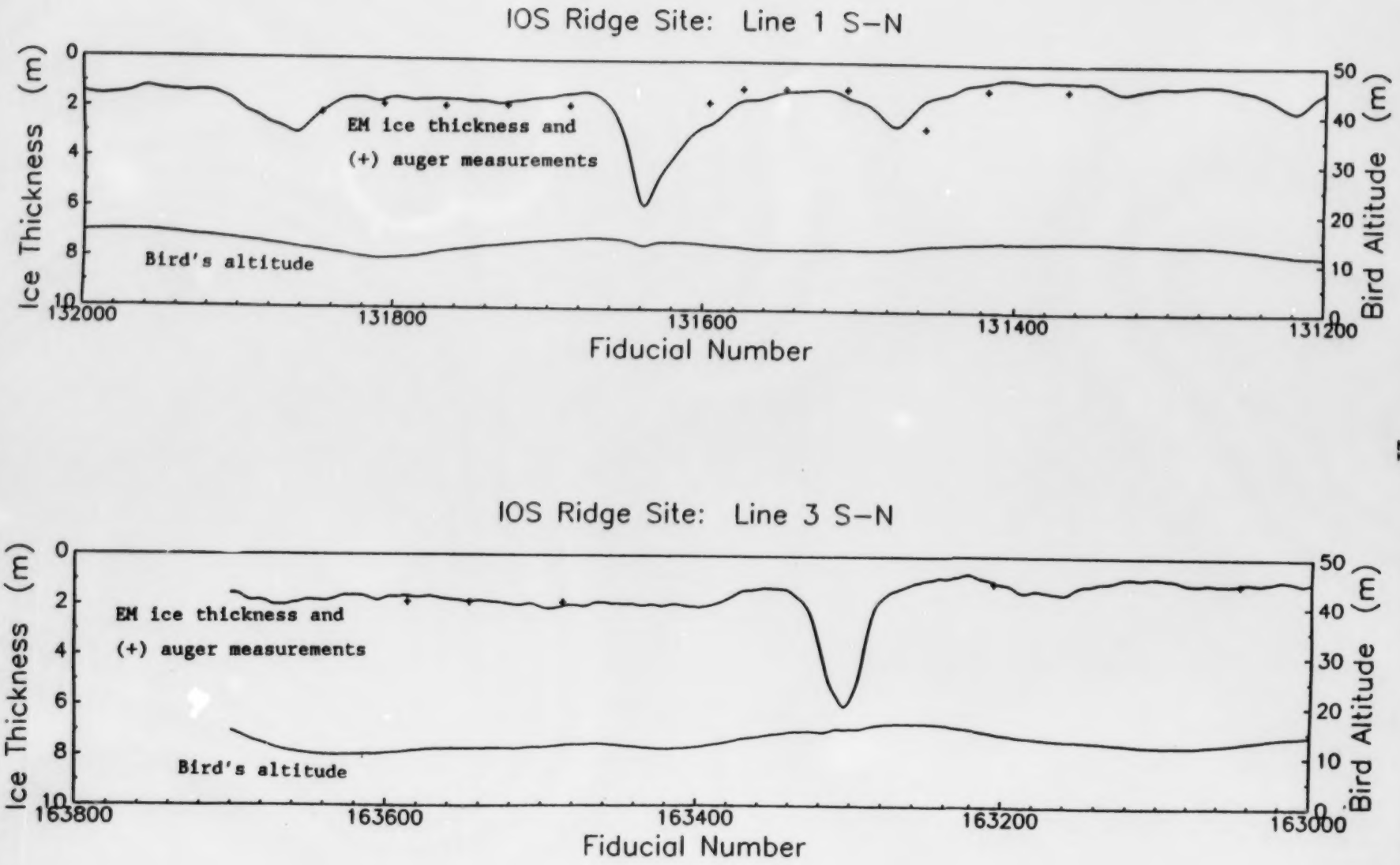

Figure 4. Electromagnetic ice plus snow thickness plots of the IOS pressure ridge.

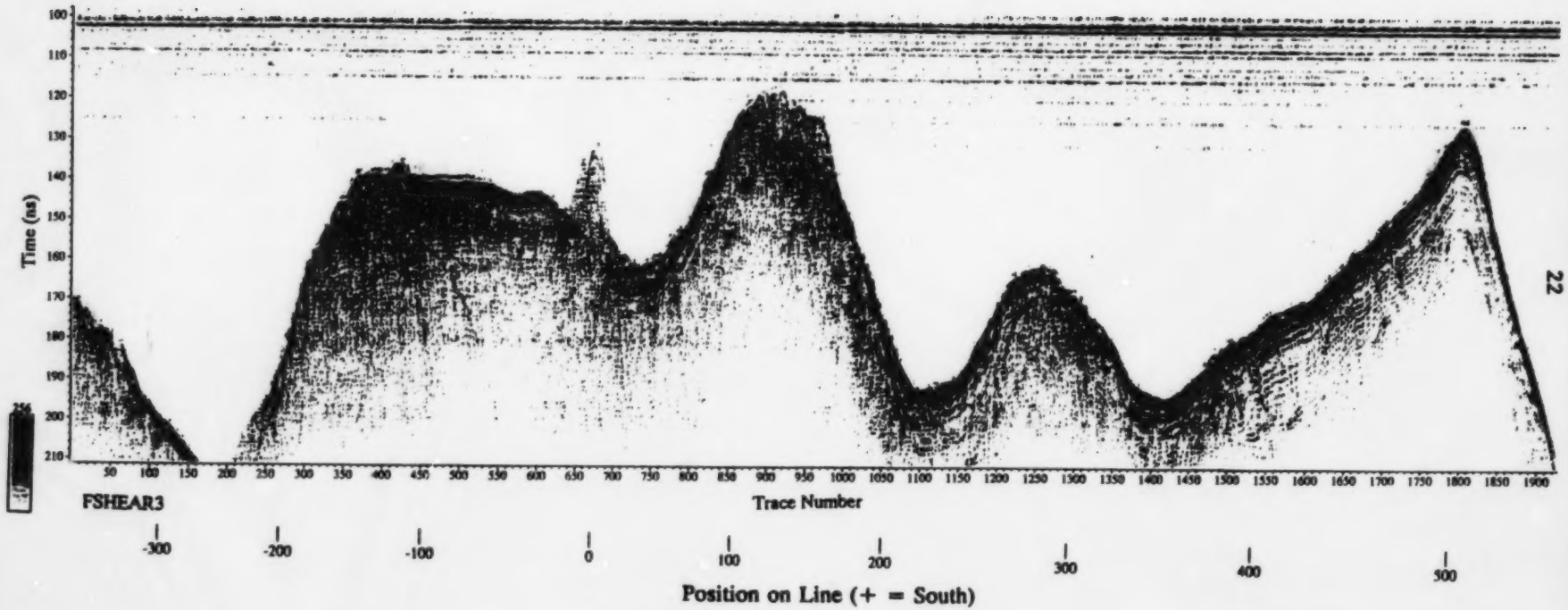

Figure 5. Raw radar profile data observed while crossing the shear ridge.

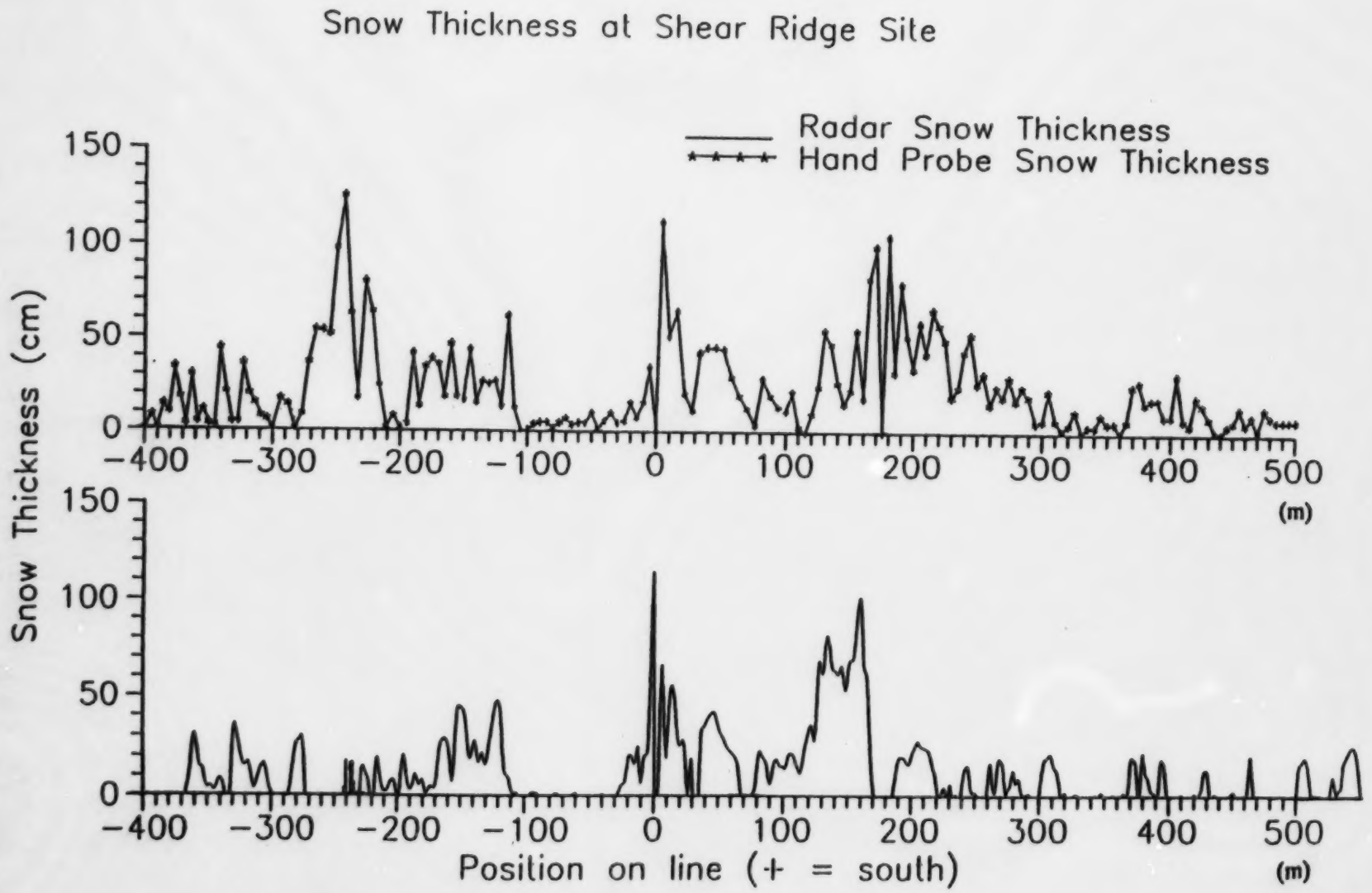

Figure 6. On-ice observed snow depth cross-section from the shear ridge (upper panel) compared to processed radar data over the same site (lower panel). Site is shown in Fig. 7.

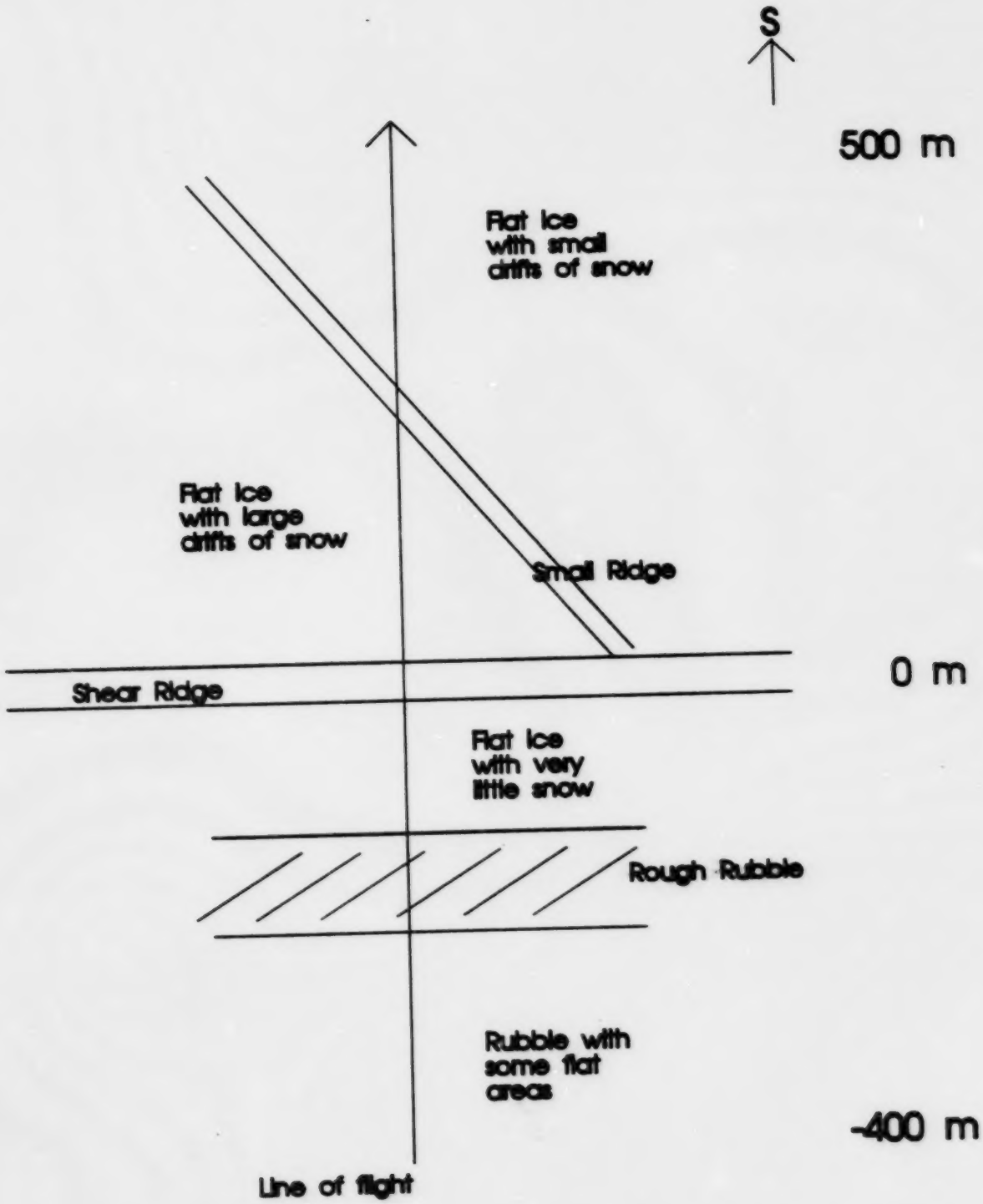

Figure 7. Sketch of shear ridge site.

APPENDIX A: ICE THICKNESSES and SNOW DEPTH

A.1 Calibration Site (CS)

Latitude 70° 13′ 09.4″
Longitude 133° 08′ 48.4″

	----------ICE(cm)----------					-----SNOW(cm)-----		
Stn#	Apr08	Apr12	Apr15	Apr20	Diff.	Apr08	Apr20	Diff
8	97	100	102	104	+7	5	4	-1
7	110	114	106	111	+1	3	3	0
6	100	-	-	95	-5	7	6	-1
5	98	-	-	104	+6	4	6	+2
4	98	-	-	104	+6	5	1	-4
3	100	-	-	104	+4	6	4	-2
2	99	-	-	104	+5	4	3	-1
1	100	-	-	104	+4	4	2	-2
-1*	100	-	-	104	+4	4	5	+1
-2*	100	-	-	109	+9	4	2	-2
MEAN	100			104	+4.5	4.5	3.5	-1.0

* Stations occupied on April 9

A.2 North-South line centred at Stn #1 (April 8)

	Stn#11	-	Stn#12	-	Stn#1	-	Stn#13	-	Stn#14
snow(cm)	6	4	4	6	4	4	8	4	4
ice (cm)	98	-	100	-	100	-	98	-	100

-Stations -2 to 8 in East-West direction at 100m spacing
-Stn#8 in East and Stn#2 in West
-Early rafting when ice was 11cm thick occurred at Stns#'s 2, 7 and 8
-Stations 11 to 14 in North to South direction at 50m spacing
-Stn#11 in North and Stn#14 in South
-65 to 80 cm thick ice blocks in rubble field North of refrozen polynya
-Total length 900m and width 270m

A.3 I.O.S. Pressure Ridge (PR)

	April 13	April 15	April 16	April 20
Latitude	70° 28′ 34.4″	70° 31′ 51.5″	70° 32′ 16.9″	70° 28′ 32.8″
Longitude	133° 54′ 51.5″	134° 06′ 13.8″	134° 12′ 50.8″	134° 11′ 30.1″

Stn#	snow	ice	Stn#	snow	ice	Stn#	snow	ice
0	35	182	10	16	174	20	8	176
1	14	-	11	8	-	21	10	-
2	16	-	12	22	-	22	7	-
3	10	-	13	10	-	23	12	-
4	18	-	14	8	-	23.5	12	-
5	8	176	15	10	174	24	22	-
6	8	-	16	10	-	24.5	90	-
7	7	-	17	6	-	25	--RIDGE--	
8	10	-	18	18	-			
9	20	-	19	14	-			
10	14	174	20	8	176			

Stn#	snow	ice	Stn#	snow	ice	Stn#	snow	ice
25	-- RIDGE--		35	2	105	45	45	218
26	40	-	36	2	-	46	3	-
27	10	-	37	1.5	-	47	5	-
28	2	-	38	2	-	48	6	-
29	1.5	-	39	2	-	49	2	-
30	1	165	40	5	100	50	2	102
31	1	-	41	5	-	51	2	-
32	3	-	42	5	-	52	2	-
33	2	106	43	1	-	53	2	-
34	5	-	44	2	-	54	1.5	-
35	2	105	45	45	218	55	3	100

-Transect south to north; snow stations 10m apart, ice stations 50m apart
-Length south of ridge Stns 0-25 is 250m; north of ridge Stns 25-55 is 300m
-Rough ice cover between Stns 40 to 48 with ice blocks 30cm thick
-A second raft started at Stn 33 after 2m of water at a depth of 340cm
-Snow depths sampled on April 13 and ice thicknesses on April 16

A.4 ICE ROAD (IR)

Latitude 69° 27"
Longitude 130° 10"

Depth 325cm (Stn7)

Stn#	snow	ice	Stn#	snow	ice	Stn#	snow	ice
0	34	178	15	10	202	30	30	178
1	24	-	16	15	-	31	27	-
2	16	-	17	34	-	32	42	-
3	6	-	18	10	-	33	95	-
4	13	-	19	80	-	34	58	-
5	24	190	19.2	90	-	35	38	183
6	12	-	20	32	204	36	37	-
7	10	-	20.1-24.9	ICE	ROAD	37	20	-
8	18	-	24.9	0	195	38	22	-
9	6	-	25	75	-	39	24	-
10	20	204	25 2	160	-	40	20	198
11	30	-	26	120	-	41	25	-
12	16	-	27	50	-	42	17	-
13	20	-	28	27	-	43	16	-
14	14	-	29	85	-	44	22	-
15	10	202	30	30	178	45	20	193

-Transect across ICE ROAD runs South (Stn# 0) to North (Stn# 45)
-Snow Stns 5m apart; ice Stns 25m apart; Ice Road 25m wide
-Total length including ice road is 225m
-3 snow ridges north of Road: 160cm Stn# 25.2, 90cm Stn# 29.1 and 145cm Stn# 32.5
-Snow depths sampled on April 7 and ice thicknesses on April 10

APPENDIX B: ICE and SURFACE WATER SALINITY DATA

I. ICE ROAD STATION

B.1 Ice Road Station #7 - IR7

Latitude 69° 27′
Longitude 133° 10′

April 10, 1991
Ice 197cm(est)
Snow 10cm
Depth 3m

Sample#	Depth cm	Bottle#	Sal. ppt*
IR7.1	10-15	64649	0.5 (1.235)
IR7.2	25-30	64670	0.0 (0.241)
IR7.3	75-80	64669	0.0 (0.114)
IR7.4	120-130	64656	0.0 (0.053)
IR7.5	Water	06510	0.0
IR7.6	Water	64634	0.0

*determined by refractometer; in brackets redone with autosalometer

- -

II. EM CALIBRATION STATIONS (Refrozen Lead)

B.2 Calibration Site #7 - CS7

Latitude 70° 13′ 09.4′
Longitude 133° 08′ 48.4′

April 12, 1991
Ice 114cm
Snow 4cm
Depth 40m

Sample#	Depth cm	Bottle#	Sal. ppt
CS7.1	6-10	64671	10.0 (11.334)
CS7.2	22-27	64672	7.5 (8.500)
CS7.3	40-45	--	8.0
CS7.4	60-65	--	10.0
CS7.5	80-85	64693	10.0 (10.435)
CS7.6	Water	--	32.0

- -

B.3 Calibration Site #8 - CS8

Latitude 70° 13′ 09.4′
Longitude 133° 08′ 48.2′

April 8, 1991
Ice 97cm
Snow 4.5cm
Depth 40m

Sample#	Depth cm	Bottle #	Sal. ppt
CS8.1	6-10	--	8.0
CS8.2	32-35	--	8.0
CS8.3	52-55	--	9.0
CS8.4	72-75	--	17.0(wet)
CS8.5	Water	64637	32.5

B.4 Calibration Site #1 - CS1

April 9, 1991
Ice 100cm
Snow 4cm
Depth 40m

Latitude 70° 13′ 09.4′
Longitude 133° 08′ 48.4′

Sample	Depth cm	Bottle #	Sal. ppt
CS1.1	10-14	--	9.5
CS1.2	25-30	--	8.5
CS1.3	45-50	--	8.5
CS1.4	70-75	--	8.0
CS1.5	85-90	--	14.5(wet)
CS1.6	Water	64640	32.5 (32.157)

B.5 Calibration Site #-2 - CS2

April 21, 1991
Ice 109cm
Snow 2cm
Freeboard 10cm
Depth 40m

Latitude 70° 13′ 09.6′
Longitude 133° 08′ 46.3′

Sample	Depth cm	Bottle #	Sal. ppt
CS2.1	10-15	64697	18.0 (19.643;wet)
CS2.2	30-35	64652	7.0 (8.691)
CS2.3	50-55	64646	6.5 (8.321)
CS2.4	60-65	64699	9.0 (10.321)

III. IOS PRESSURE RIDGE STATIONS

B.6 IOS Pressure Ridge Station #5 - PR5

April 14, 1991
Ice 176cm
Snow 8cm
Depth 60m

Latitude 70° 28′ 34.4′
Longitude 133° 54′ 51.5′

Sample	Depth cm	Bottle #	Sal. ppt
PR5.1	5-10	64694	3.0 (3.877)
PR5.2	20-25	64695	5.0 (5.956)
PR5.3	60-65	64696	6.0
PR5.4	80-85	64621	6.5
PR5.5	100-110	64620	6.5
PR5.6	130-140	64616	6.0
PR5.7	160-170	64617	9.5 (10.407)
PR5.8	Water	64639	32.0 (32.096)

B.7 IOS Pressure Ridge Station #7 - PR7

Latitude 70° 28″ 34.5′
Longitude 133° 54″ 51.5′

April 14, 1991
Ice 106cm
Snow 2cm
Depth 60m

Sample	Depth cm	Bottle #	Sal. ppt
PR7.1	10-15	64618	14.0 (14.364)
PR7.2	25-30	64659	6.0
PR7.3	45-50	64653	6.0 (6.123)
PR7.4	70-75	64650	8.5 (9.051)
PR7.5	95-105	64700	10.0 (10.594)

B.8 IOS Pressure Ridge Ice Block Stn.#1 - PR1

Latitude 70° 28″ 32.8′
Longitude 134° 11″ 30.1′

April 20, 1991
Block 25/30cm
Snow 5cm
Depth 60m

Sample	Depth cm	Bottle #	Sal. ppt
PR1.1	10-15	--	2.0
PR1.2	20-25	--	3.5

B.9 IOS Pressure Ridge Ice Block Stn.#2 - PR2

Latitude 70° 28″ 32.8′
Longitude 134° 11″ 30.1′

April 20, 1991
Block 25/30cm
Snow 5cm
Depth 60m

Sample	Depth cm	Bottle #	Sal. ppt
PR1.1	10-15	--	4.0
PR1.2	20-25	--	6.0

IV. SHEAR RIDGE STATIONS

b.10 Shear Ridge Stn.#11 - SR11

Latitude 6[illegible]° 53″ 17′
Longitude 133° 01″ 44′

April 9, 1991
Ice 172cm
Snow 8cm
Depth 10m

Sample#	Depth cm	Bottle#	Sal. ppt
SR11.1	Water	64636	7.5 (7.894)

B.11 Shear Ridge Stn.#9 - SR9**

April 16, 1991
Ice 214/274cm
Snow 16cm
Depth 10m

Latitude 69° 53′ 37.0′
Longitude 133° 01′ 04.4′

Sample	Depth cm	Bottle #	Sal. ppt
SR9.1	5-10	64668	6.5 (6.850)
SR9.2	20-25	64667	7.5 (8.145)
SR9.3	45-50	--	5.0
SR9.4	70-75	--	5.5
SR9.5	110-120	64666	5.0 (5.207)
SR9.6	160-170	--	5.5

**CTD station of Hydrography

- -

B.12 Shear Ridge Stn.#1 - SR1**

April 16, 1991
Ice 164/162cm
Snow 15cm
Depth 10m

Latitude 69° 53′ 07.0′
Longitude 133° 01′ 04.4′

Sample	Depth cm	Bottle #	Sal. ppt
SR1.1	10-15	64665	9.5 (9.667)
SR1.2	20-25	64664	10.0 (9.916)
SR1.3	45-50	--	7.0
SR1.4	65-70	--	6.5
SR1.5	90-100	64663	5.5 (5.586)

**CTD station of Hydrography

- -

B.13 Shear Ridge Stn.#3 - SR3

April 16, 1991
Ice 168cm
Snow 7cm
Depth 10m

Latitude 69° 53′ 17.0′
Longitude 133° 01′ 04.4′

Sample	Depth cm	Bottle #	Sal. ppt
SR3.1	Water	64648	5.5 (5.436)

- -

B.14 Shear Ridge Stn.#7 - SR7

April 16, 1991
Ice 188cm
Snow 1cm
Depth 10m

Latitude 69° 53′ 29.0′
Longitude 133° 01′ 04.4′

Sample	Depth cm	Bottle #	Sal. ppt
SR7.1	Water	64654	27.5 (27.871)

B.15 Shear Ridge Stn.#8 - SR8

April 16, 1991
Ice 158cm
Snow 2cm
Depth 10m

Latitude 69° 53" 34.0'
Longitude 133° 01" 04.4'

Sample	Depth cm	Bottle #	Sal. ppt
SR8.1	Water	64698	27.0

- -

B.16 Shear Ridge Ice Block - SR6

April 21, 1991
Blocks 100cm
Snow 5cm
Depth 10m

Latitude 69° 53" 25.0'
Longitude 133° 01" 04.4'

Sample	Depth cm	Bottle #	Sal. ppt
SR6.1	25-30	64698	1.5
SR6.2	60-65	--	2.0
SR6.3	80-85	--	2.0

- -

V. ICE STATIONS

B.17 Ice Station #2 - IS2

April 9, 1991
Ice 126cm
Snow 6cm
Depth 35m

Latitude 70° 03" 29'
Longitude 133° 04" 29'

Sample#	Depth cm	Bottle#	Sal. ppt
IS2.1	Water	64635	32.0

- -

B.18 Ice Station #5 - IS5

April 12, 1991
Ice 180cm
Snow 5cm
Depth 35m

Latitude 70° 05" 19.6'
Longitude 133° 16" 28.7'

Sample	Depth cm	Bottle #	Sal. ppt
IS5.1	Water	64642	31.5

B.19 Ice Station #6 - IS6

April 12, 1991
Ice 184cm
Snow 4cm
Depth 35m

Latitude 70° 05′ 19.5′
Longitude 133° 16′ 28.7′

Sample	Depth cm	Bottle #	Sal. ppt
IS6.1	Water	64647	32.0

- -

B.20 Ice Station #7 - IS7

April 13, 1991
Ice Open lead
Snow 0cm
Depth 40m

Latitude 70° 15′ 11.2′
Longitude 133° 43′ 11.2′

Sample	Depth cm	Bottle #	Sal. ppt
IS7.1	Water	64661	32.0

- -

B.21 Ice Station #8 - IS8**

April 19, 1991
Ice 174cm
Snow 21cm
Freeboard 11cm
Depth 20m

Latitude 69° 53′ 37.0′
Longitude 133° 01′ 04.4′

Sample	Depth cm	Bottle #	Sal. ppt
IS8.1	15-20	--	8.0
IS8.2	40-45	--	6.0
IS8.3	60-65	--	9.0
IS8.4	80-85	--	6.5
IS8.5	100-110	--	8.5

**CTD station of Hydrography (20cm thick blocks in nearby ridge)

APPENDIX C: REFRACTOMETER-AUTOSALOMETER SALINITY COMPARISON

		SALINITY (ppt)		
#	SAMPLE #	REFRACT.	AUTOSAL.	DIFF.
1	64617	9.5	10.407	-0.907
2	64618	14.0	14.364	-0.364
3	64636	5.5	5.894	-0.394
4	64639	32.0	32.096	-0.096
5	64640	32.5	32.157	+0.343
6	64646	6.5	8.321	-1.821
7	64648	7.5	7.436	+0.064
8	64649	0.5	1.235	-0.735
9	64650	8.5	9.051	-0.551
10	64652	7.0	8.691	-1.691
11	64653	6.0	6.123	-0.123
12	64654	27.5	27.871	-0.371
13	64656	0.0	0.053	-0.053
14	64663	5.5	5.586	-0.086
15	64664	10.0	9.916	+0.084
16	64665	9.5	9.667	-0.167
17	64666	5.0	5.207	-0.207
18	64667	7.5	8.145	-0.645
19	64668	6.5	6.850	-0.350
20	64669	0.0	0.114	-0.114
21	64670	0.0	0.241	-0.241
22	64671	10.0	11.334	-1.334
23	64672	7.5	8.500	-1.000
24	64693	10.0	10.435	-0.435
25	64694	3.0	3.877	-0.877
26	64695	5.0	5.956	-0.956
27	64697	18.0	19.643	-1.643
28	64699	9.0	10.321	-1.321
29	64700	10.0	10.594	-0.594
			mean*	-0.57

* Another set of 25 ice and water samples from the Labrador shelf had a similar mean difference of -.50 indicating that the refractometer readings are consistantly low by 0.5 ppt and should be adjusted by that amount.

APPENDIX D: WMO ICE REMOTE SENSING WORKSHOP PAPER

OPERATIONAL AIRBORNE SEA ICE THICKNESS MEASUREMENT SYSTEM

by

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Presented at

2nd WMO Operational Ice Remote Sensing Workshop
Ottawa, Ontario
September 10-13, 1991

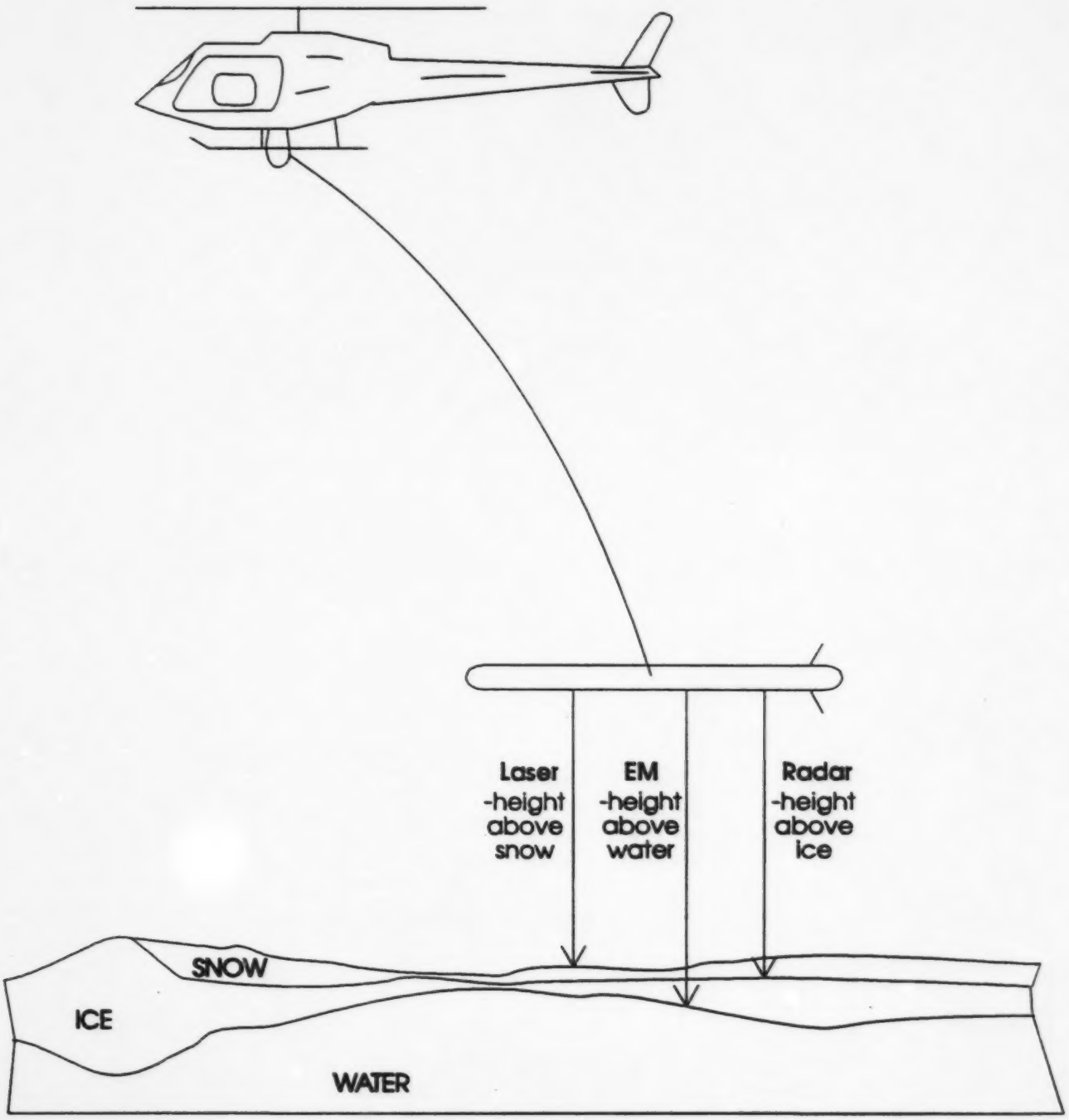
OPERATIONAL AIRBORNE SEA ICE THICKNESS MEASUREMENT SYSTEM

ABSTRACT

Research and development of airborne sea ice thickness measurement has been conducted in Canada for over 15 years, particularly towards development of a sensor that could support icebreaker activities. Current efforts are focused on a combined electromagnetic (EM)-radar-laser sensor which is towed in a bird about 30 m below a helicopter and about 30 m above the ice surface. It is anticipated that this system will become fully operational within about two years.

Tests of this technology have been performed both in the Arctic and off Canada's east coast over a wide variety of ice types. Comparisons with surface measurements have been very good.

The system is housed in a bird about 0.4 m diameter and 4 m long, weighing about 125 kg, which can be flown at up to 150 kph. Operator electronics weighing about 50 kg are housed in the helicopter and can be easily removed for other missions. Ice thickness output is real-time. Ice thickness measurement range is approximately 0.2 to 20 m with an accuracy of the greater of $\pm 5\%$ or ± 0.1 m. Snow thickness (dry snow) can be measured to within $\pm$ 10%. Ice strength can also be estimated from the electrical conductivity of the ice.

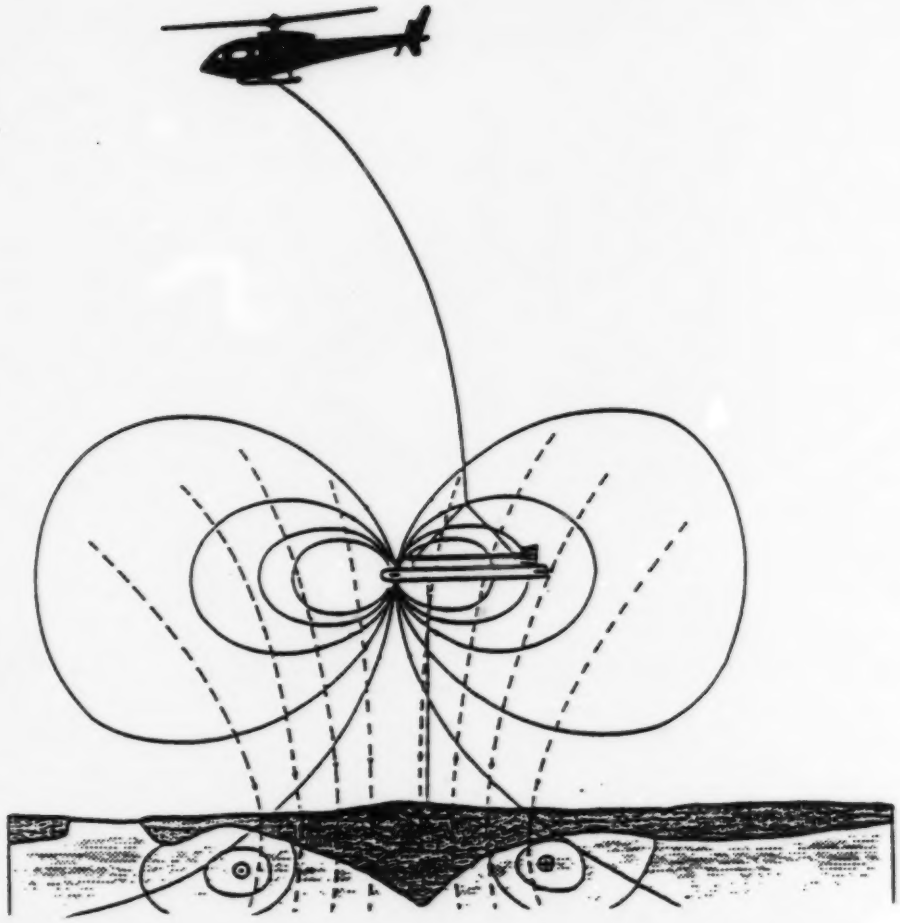

Laser
-height
above
snow
EM
-height
above
water
Radar
-height
above
ice
SNOW
ICE
WATER

Importance of Sea Ice Thickness Measurements

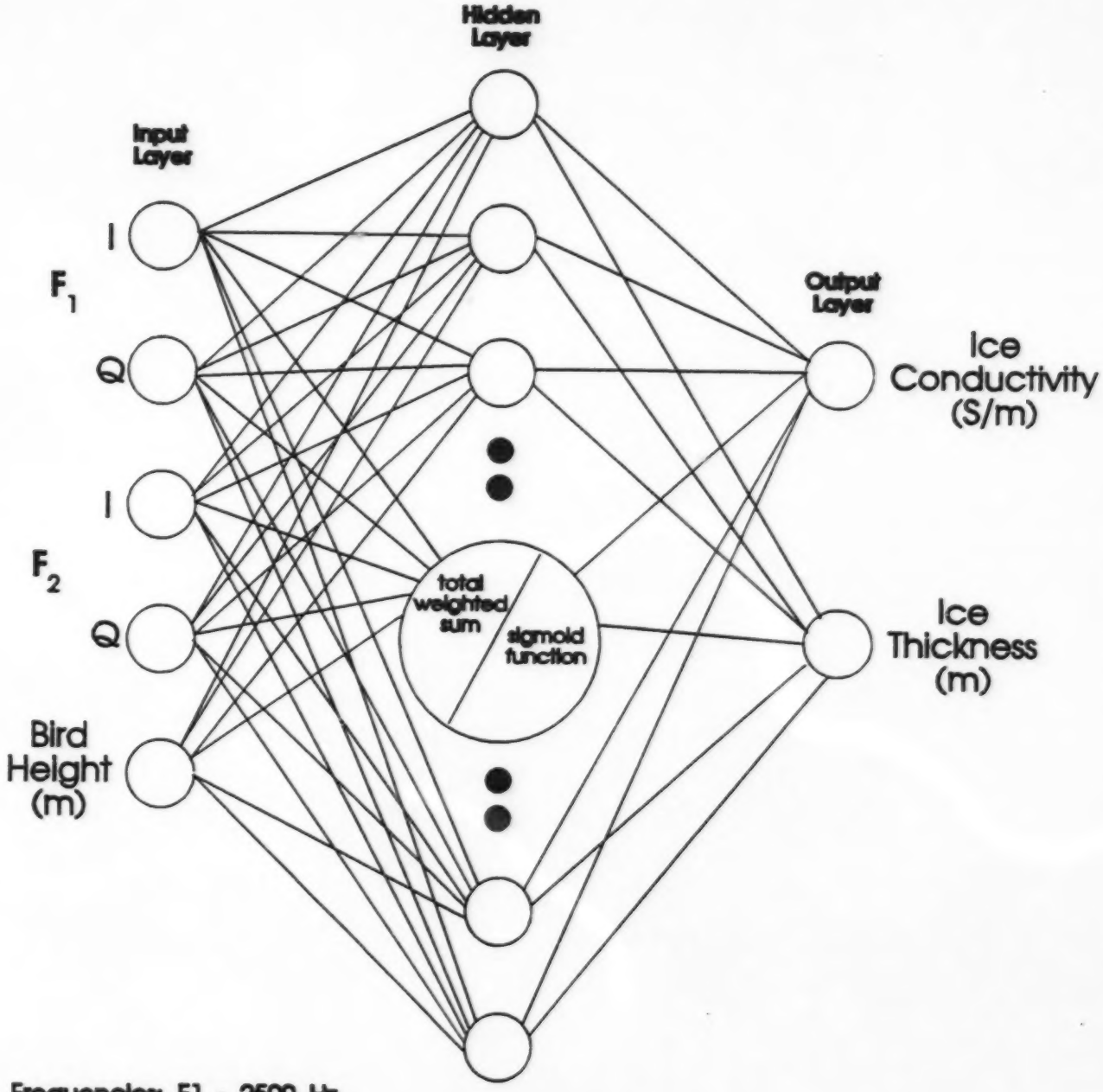
- Icebreaker operations
- Over-ice logistics
- Ice load forces
- Climatology studies
- Defence
- Icebreaker trials

History of Canadian Airborne Ice Thickness Sensor Development

- 1970's
  - Impulse radar studies; C-CORE, CRC, NRC
  - Synthetic pulse radar developed; MPB Technologies
  - Step-frequency radar; University of Toronto
- 1983 - 85 - Feasibility studies; Canpolar
- 1986 - 88 - Technology evaluation; Canpolar - Geotech
- 1989 - 91 - Preproduction prototype; Aerodat - Canpolar



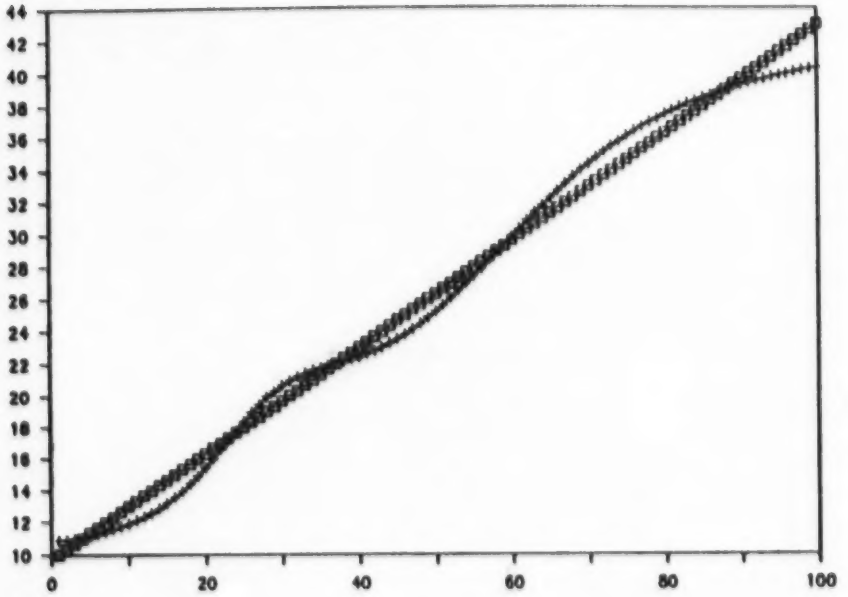
1-D Neural Network with Ice Conductivity



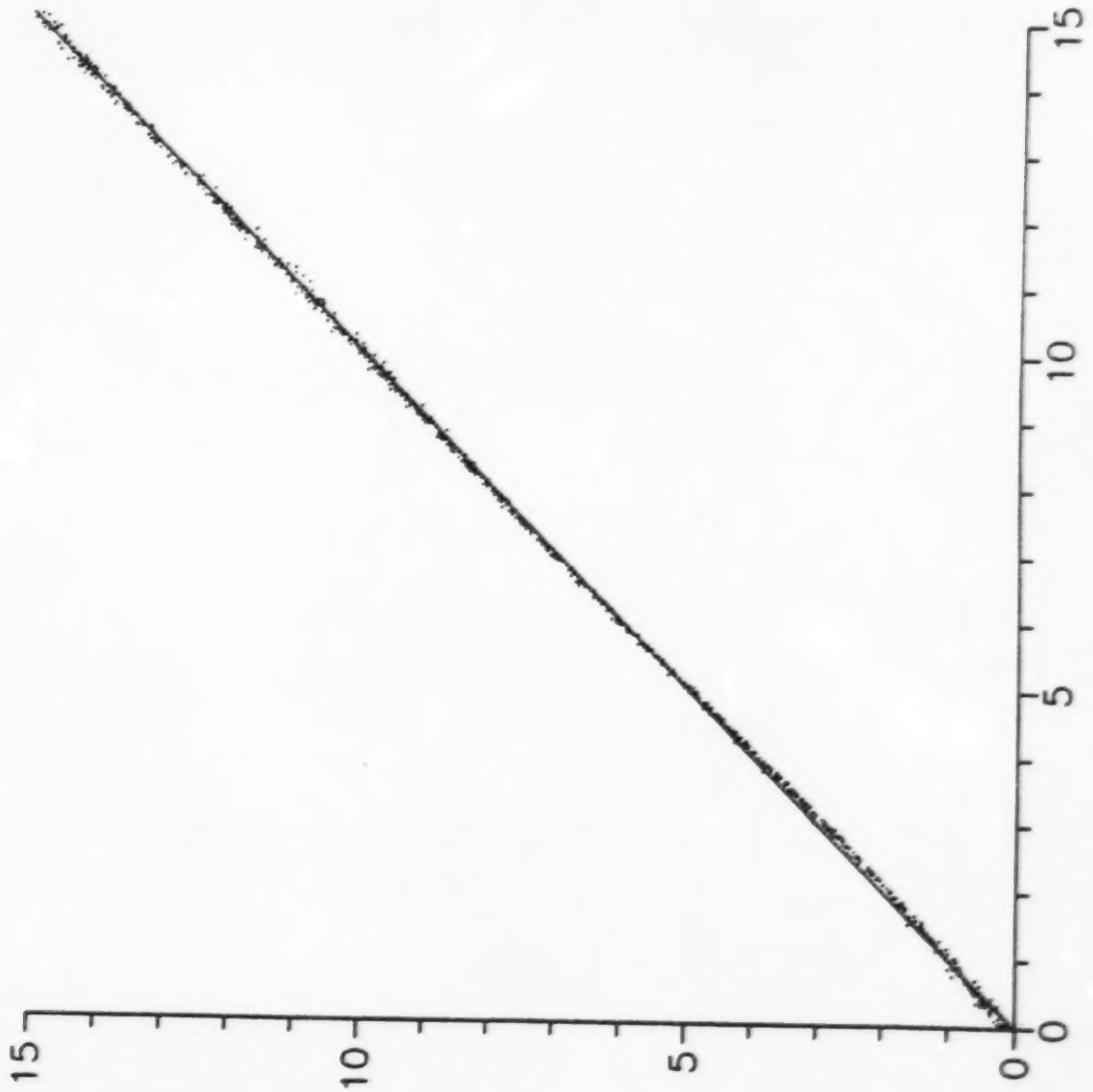
Frequencies: F1 - 2500 Hz
F2 - 94000 Hz

Altitude: Random from 10 m to 30 m
Ice thickness: Random from 0 m to 15 m
Ice Conductivity: Random from 0.003 S/m to 0.3 S/m

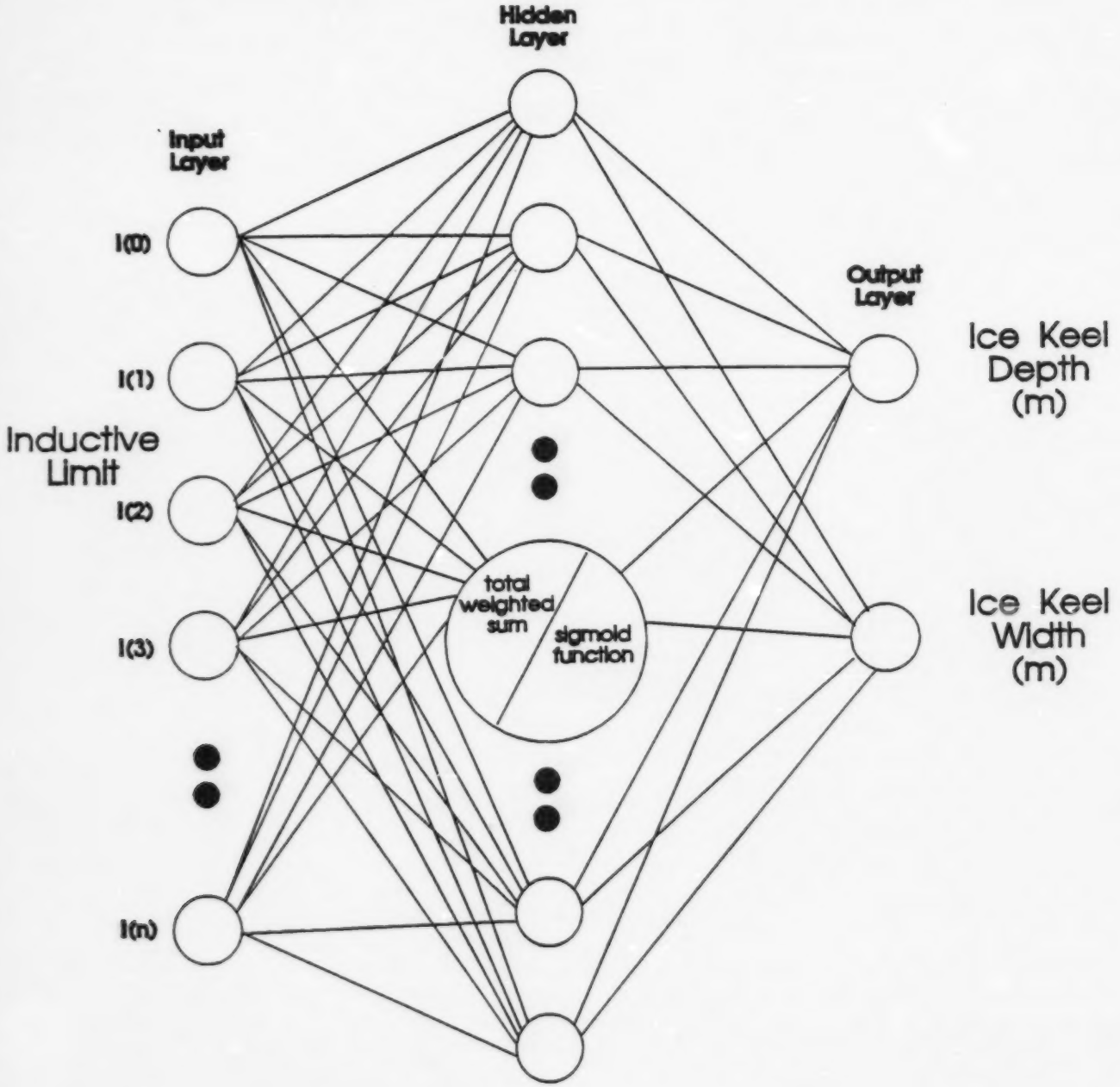
Coil separation - 3 m
Sea water conductivity - 2.5 S/m



d) 15 neurons, 1% tolerance, normalized from -5 to 60.


25 neurons, .01 tolerance
F1 only
15
10
5
0
0
5
10
15

Neural Network for 2-D Inversion of Ice Keels



Altitude: 20 m
Keek Width: Random from 10 m to 30 m
Keel Depth: Random from 5 m to 20 m
Coil separation - 3 m
Input points: from -100 m to 100 m over ice keel

Keel Shape $= De^{-(4\ln 2)\left(\frac{N}{W}\right)^2}$

Aerodat - Canpolar Ice Thickness Sensor System Characteristics - Ice

Parameter	Specification
Ice types	All level sea ice, most ridges
Ice thickness range	0.2 to 20 m
Ice thickness accuracy	$\pm$ 5% or 0.1 m (greater of)
Minimum resolvable variation	0.05 m
Snow thickness range	0.3 to 5 m (dry snow only)
Snow thickness accuracy	$\pm$ 10%
Minimum resolvable variation	0.05 m
Ice strength range	Warm, saline to cold, fresh (?)
Ice strength accuracy	$\geq$ 3 categories (?)

Aerodat - Canpolar Ice Thickness Sensor System Characteristics - Data

Parameter	Specification
Data recording	Digital, on board
Data inversion	Real-time, automatic
Data display	Ice properties, time, and position overlaid on flight path video Hard copy strip chart
Calibration and drift correction	Automatic, built-in
Debriefing station on ship	Integrated with other sensors (?) Visual overlay on video

Aerodat - Canpolar Ice Thickness Sensor System Characteristics - Equipment

Parameter	Specification
Aircraft	MBB BO105, Bell 206B, or larger
Installation on aircraft	Bolt on, bolt-off
Flying conditions	< 40 knots wind speed
Flying altitude - helicopter	40 to 70 m
Flying altitude - bird	< 30 m
Flying speed	≤ 150 kph
Horizontal footprint	Approximately bird altitude
Horizontal sampling rate	10 - 20 samples/second
Electronics size	0.5 x 0.5 x 1.0 m
Electronics weight	50 kg
Power requirement	20A @ 28 VDC
Bird size	< 0.4 m diameter x 4 m long
Bird weight	Approximately 125 kg
Tow cable	30 m, hook deployable

Future Plans

- PRE-PRODUCTION PROTOTYPES AVAILABLE FOR FEASIBILITY DEMONSTRATIONS
- PRODUCTION PROTOTYPE BEING PLANNED FOR APPROXIMATELY 1993
- FUNCTIONALLY SIMILAR, BUT HARDENED FOR OPERATIONAL USE

APPENDIX E: PAPER BY R.B. BOWEN

Field Testing of a State of the Art Airborne Remote Sensing System on a First Year Ice Ridge

ROBERT G. BOWEN, Department of Geography, University of Victoria, Victoria, B.C.

Abstract:

One dimensional and two dimensional interpretation techniques have been applied to the ice thickness results obtained from a state of the art airborne remote sensing system, field tested over a first year ice ridge. This airborne system combines the technology of a laser altimeter, an impulse radar and an electromagnetic induction sounding system in an attempt to accurately measure irregular ice geometry. Preliminary evaluation of this system is based on a volumetric comparison of the airborne interpreted data with extensive ground truth data obtained from submersible sonar surveys and topside surveys. 2-D interpretation of the airborne data yield volumetric results that are very close to the ground truth data.

Sea ice pressure ridges provide excellent study sites to examine pack ice driving forces and associated ridge building processes. The geometry of pressure ridges gives a static account of a series of dynamic processes that occurred during the ridge building event(s). Ridge geometry may also provide valuable clues as to the driving forces responsible for ridge formation.

Common to all geophysical studies involving sea ice is the determination of ice thickness. This becomes especially difficult in ridged ice where consolidated and unconsolidated rubble extend well below the adjacent level ice thickness. Unfortunately, at present, there are no spaceborne remote sensing techniques capable of measuring ice thickness directly (Shuchman and Onstott,1990). Airborne remote sensing systems such as impulse radar(Rossiter and Lalumiere,1988) or electromagnetic induction (Kovacs and Holladay,1989) have been used on level ice with success; however, these instruments have consistently underestimated ridge geometry. Measurement of the exposed topside or sail of ridges is straight forward and has been carried out by stereo air photo interpretation and theodolite surveys; however, the measurement of keel geometry has been limited to fixed upward looking sonar systems, submarine tracks and more recently, sonar equipped submersibles. All of these techniques are time consuming, costly and require large amounts of post processing time.

An effort has been made to develop a state of the art airborne remote sensing system capable of real time ice thickness measurements of irregular features. This system, operated by Aerodat Limited with radar equipment from Canpolar Limited, integrates three remote sensing systems in an attempt to measure surface and subsurface geometry of first year ice ridges. The development of this new system is part of an ongoing research program designed to investigate the dynamics of pack ice driving forces, ice/ice and ice/structure interactions. This broader research program was developed and funded by the Panel on Energy Research and Development (PERD) which has coordinated the efforts of government research institutes, private industry and university participation.

This paper examines the preliminary findings of the April 1991 field testing program carried out on a first year ice ridge located approximately 60 km north of Tuktoyaktuk. In order to evaluate the performance of the airborne system, it was necessary to carry out extensive ground truthing which involved both sail and keel surveys. Ridge geometry surveys were carried out by a research team from the Arctic Group of the Institute of Ocean Sciences(IOS) Sidney,B.C. In addition, snow thickness, salinity and level ice thicknesses were measured near the ridge by Dr. Simon Princenberg of Bedford Institute of Oceanography, Dartmouth, Nova Scotia. In this paper, only the IOS survey data will be presented and compared to the preliminary analysis of the data obtained from the airborne system.

Airborne Survey Instrumentation

The overall requirement for the design of an airborne system capable of resolving ridge geometry was to select and fine tune instrumentation that could accurately detect the air/snow, snow/ice and ice/water interfaces. The state of the art system used in this field study was the next step in a line of helicopter towed instrumented birds that have been used over ice. Unlike previous surveys, this bird had a number of improvements and additions designed specifically to detect the irregular geometry of ice ridges. This new design incorporated a laser altimeter to measure bird to snow distance, an impulse radar to measure snow thickness and an electromagnetic (EM) induction sounding system to measure ice thickness. Although these systems have been used before, they have never been packaged together. Frequencies for the impulse radar and the EM system were adjusted to optimize their ability to detect boundary interfaces. Both of these instruments have significantly different frequency signals and therefore different attenuation rates through snow and ice. All three of these instruments were housed within a rigid 3.5 m Kevlar bird and towed below a Bell 206 helicopter. Data acquisition for the remote sensing system was controlled by a 386 computer onboard the helicopter. During flight, each of the instruments were designed to measure one of the three interfaces.

The laser altimeter, which is essentially a laser range finder, targeted the air/snow interface. It was installed within the bird at the bottom centre and was directed downwards perpendicular to the plane of the bird. This instrument is capable of making 40 bird to surface measurements per second with a listed manufacturer's accuracy of approximately 5 cm. The sampling rate utilized for this test series was 10 Hz.

The impulse radar system supplied by Canpolar limited was developed by Geophysical Survey Systems Inc (GSSI), and includes an SIR System 7 timing control unit and a 3102DP 500 Mhz transducer. The transducer was mounted at the aft of the bird. The system's high frequency pulse, transmitting at pulse durations of 2-3 ns, attenuates rapidly in sea ice. The design philosophy was that the pulse would travel relatively unimpeded through the top layer of snow and reflect off the snow/ice interface. By subtracting the accurate laser data of the air/snow interface from the impulse radar data of the snow/ice interface, the snow thickness could be calculated. This is the first application of an airborne impulse radar for snow thickness measurements. The scan rate selected for this instrument was 12 Hz and the analog output was recorded on the HQ audio track of the flight path imagery videotape recorder during profiling operations at the ridge site. The illuminated

footprint of the impulse radar is approximately equal to the flying height of the bird as the radiated pattern is basically that of a dipole antenna(Rossiter and Lamumiere,1988).

The Aerodat Limited electromagnetic induction sounding system used for this project was designed for the Transport Development Centre of Transport Canada. This survey was the first Arctic field test of the system. Airborne electromagnetic sounding technology has been in operation for many years in the geological exploration industry. It is only within the last seven years that this technology has been modified for ice thickness studies(Kovacs and Holladay,1989). The principle components used in this system are a set of transmitter and receiver coils. The transmitter coil was mounted in the forward section of the bird and the receiver coil at the extreme aft. The transmitted electromagnetic field was emitted from the forward coil and was directed at the ice surface. The strong primary field penetrates through the ice inducing eddy currents in the electrically conductive ice and water masses. These eddy currents generate secondary magnetic fields which are detected by the receiver coil (Holladay et al,1990b; Lintz and Sumonett,1976). The system can transmit at a frequency of 2.5 or 94 kHz for ice penetration. The secondary fields are primarily influenced by the geometric relationships between the system and the ice/water boundary. The secondary fields are also influenced by the electrical properties of ice and sea water. These properties for snow, ice and sea water differ with the greatest differential conductivity contrast being at the sea water/ice interface(Kovacs et al,1987). The EM system has been designed to measure the distance between the sensor and this high contrast ice/water interface to a vertical resolution of approximately 10 cm.

Pitch and roll sensors were installed within the bird in order to correct for changes in the bird attitude. A Global Positioning System (GPS) was used to record the flight path during the airborne surveys. In addition, a downward looking video camera with on screen annotated fiducial marks was used to visually track the flight path. Both the GPS and the video recordings would aid in tying down the airborne survey with the ground truth data.

Field Survey Instrumentation

The sail geometry ground truthing instrumentation consisted of a WILD T2 theodolite, a WILD Distomat 120 Electronic Distance Measuring device (EDM) with prism reflectors and a WILD RC-10 air photo camera which was flown over the area to obtain good quality stereo pairs of the ridge site.

Keel geometry surveys required the use of a Tethered Arctic Reconnaissance Submersible (TARS). The TARS, manufactured by International Submarine Engineering Limited of Vancouver B.C., utilized the following instrumentation:
(1) Acoustic Tracking System (ATS)
(2) Mesotech Sonar
(3) TARS pressure transducer.
The ATS was used to accurately track the position of the TARS as it moved under the ice. The system was designed by Nautronix and has been used extensively for numerous offshore applications such as underwater vehicle tracking, drill rig positioning and mine neutralisation tasks for the military. The specific model used for the TARS application was the Acoustic

Position Indicator, model S04 (API-S04). This system is composed of the following components:
(1) Master control unit
(2) Responder interface unit
(3) Hydrophone
(4) Mini beacon.
Trigger commands are issued from the master control unit and relayed to the responder interface unit. This unit sends coded interrogation signals to the TARS mini beacon via the umbilical cable. The mini beacon responds with an acoustic train of eight individual chirps each of which is a linear frequency sweep in the 15 to 18 kHz bands. This response pattern travels through the water and is received by a hydrophone located at the TARS entry hole. Contained within the hydrophone are six equi-spaced receiving transducers. As the eight chirps move across the hydrophone, phase differences are measured and an accurate position of the TARS is obtained. The resultant output from this system is in the form of X,Y coordinates. The Z component is also given as the mini beacon on the TARS houses a pressure transducer for determining the depth of the TARS (Nautronic ATS-S04 manual,1989).

The Mesotech sonar is an upward looking sonar system mounted on the top of the TARS. Its pulse transmits at a 675 kHz frequency and produces a narrow conical beamwidth of 1.8 degrees. The beam footprint on the underside of the ice of the Mesotech transmitting at a depth of 20 metres below the ice would be approximately 0.5 metres in diameter. Underside ice features are measured by the delay time between the initial pulse and its acoustic reply. Depth of the TARS is continually monitored by a Gulton differential pressure transducer. Pressure data are transmitted through the umbilical cable to the surface at a rate of 1Hz.

Test Program

The field testing program began April 11,1991. A first year pressure ridge was selected from aerial reconnaissance and was located at the GPS measured coordinates of 70 28.574'N and 133 54.780'W. A D.H.Twin Otter was used to shuttle equipment from Tuktoyaktuk to the site and a makeshift runway was marked out. The ridge selected was in the order of 300 metres long and varied in width from 15 to 40 metres. The sail of the ridge was largely wind swept exposing the cardhouse stacking of ice blocks of various sizes, shapes and orientations. A baseline adjacent to the longest axis of the ridge was surveyed and a coordinate system established. 192 XYZ survey points were collected using the theodolite and EDM in tandem. Survey points were carefully chosen to be representative of the somewhat irregular surface of the ridge. A number of large snow filled garbage bags visible from the air were placed on and beside the ridge and a fixed wing aircraft was flown over the area photographing the site. These garbage bags were surveyed into the topside data and acted as tie down points for post processing air photo interpretation. Two TARS entry holes were bored through the level ice adjacent to the ridge for keel surveys. Both of these entry holes were also surveyed into the topside data in order to align sail geometry to keel geometry. Sixteen survey tracks radiated out from the first hole and eighteen tracks from the second. The data acquisition system used for the submersible was a 386 laptop computer.

This computer system was located within a heated control tent on the ice. In-house software was developed to time stamp all three incoming data streams(ATS, Mesotech and pressure transducer) in order to synchronize the data for post processing alignment. Underwater video recordings were made of each track.

Seven overflights were made using the airborne remote sensing system. Five of the survey lines traversed the short axis and two overflights ran along the crest of the ridge for the entire 300 metres. Both GPS and video recordings were made during the overflights in order to tie down data to the ground survey coordinate system. The altitude of the bird over the ice varied somewhat ranging from 15 metres to well over 30 metres. The ground speed of the bird over the ridge segments was on the order of 60 km/hr.

Analysis

Post processing of ground truth data was performed at the Institute of Ocean Sciences and the University of Victoria. Air photos, supplied by NRC, were used to digitize an additional 4000 XYZ data points. Digitization of these additional data points was carried out on an AP190 analytical stereo plotter which was made available for this study by the BC Forestry Research Branch. The more than 4000 data points were used to generate a digital terrain model(DTM) of the sail geometry as displayed in figure 1.

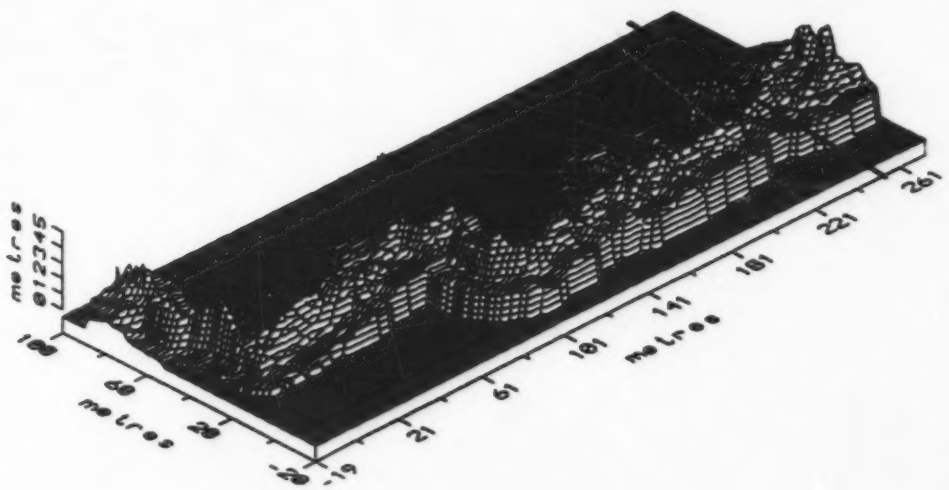


Figure 1 Topside DTM
(the line located at the 255m mark on the long axis the ridge marks the airborne survey overflight evaluated in this report)

The TARS analysis was somewhat more involved. It was necessary to use the data collected from the ATS, the Mesotech sonar and the onboard pressure transducer to determine XYZ coordinates of the keel geometry. The sampling rate for each of the instruments differed and were as follows:

(1) ATS sampled at approximately 3 second intervals
(2) Mesotech sonar sampled at 16 Hz
(3) Pressure transducer sampled at 1 Hz

Data were standardized to a common sampling rate of 2 Hz by interpolation and all three data files were merged together for each of the tracks. The speed of sound in sea water was calculated from the insitu temperature and salinity and was applied to the Mesotech two-way response times. Calculations using the Mesotech data produced data of the submersible distance to the sea water/ice interface. This distance was then subtracted from the total depth of the submersible as measured by the pressure transducer. The result of this calculation gave the depth of the ice keel relative to the sea level surface. The X and Y components of the TARS were obtained from the ATS. Figure 2 and 3 are the DTMs generated from TARS data collected at holes 1 and 2 respectively.

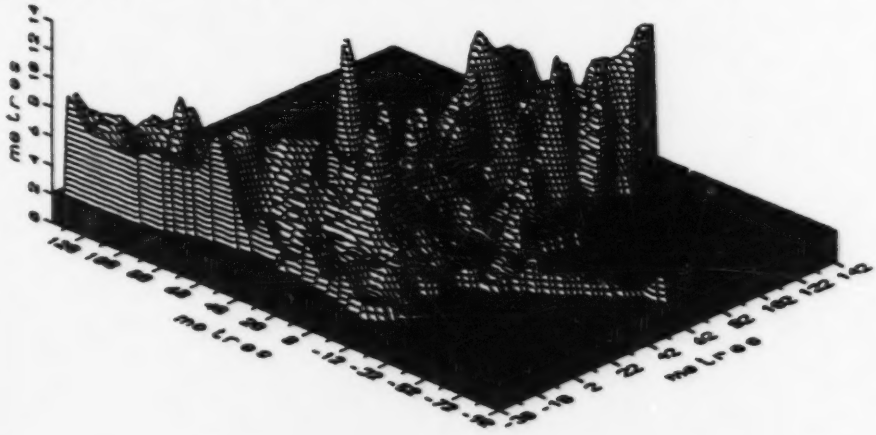


Figure 2 Keel DTM Hole #1

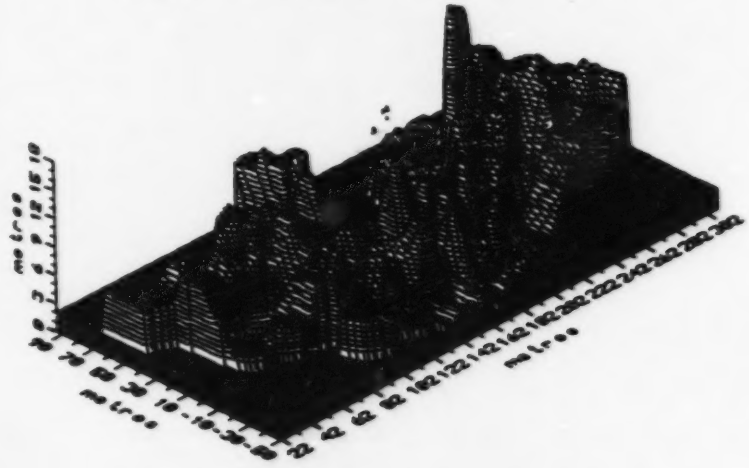


Figure 3 Keel DTM Hole #2

Analysis of selected segments of the EM data were carried out by Aerodat Limited using in-house algorithms. These processed segments were supplied by Aerodat and preliminary analysis is based on this supplied data.

The first step in analyzing the EM data required the airborne GPS readings to be tied down to the GPS readings taken on the ice. Unfortunately at the time of the airborne survey, the last on ice GPS reading had been taken many hours before. Previous on ice GPS readings taken over the course of a number of days indicated that the ice ridge and surrounding plates had significant net motion. Averaged velocities were as high as 15 cm/s. The absolute airborne GPS readings were therefore of little use; however, the relative spacings of the readings could be used to convert GPS coordinates to metres. A videotape of the overflights (also supplied by Aerodat) provided a method of tying down the airborne survey to the ground truth coordinate system. Only three of the seven overflights could be coordinated with the ground survey data as video coverage was unavailable for the first five flight lines. Accurate measurements of the bird flight path relative to the ice ridge were made using a video frame grabbing software. The on screen fiducial marks annotated onto the video and encoded with the incoming EM data served to align the data to the XY coordinate system used for the ground truth data. Of the three usable overflights, the flight line over the 255 metres mark (Figure 1;long axis) of the ridge was chosen for evaluation as the bird height was relatively low and bird flight stable. The results from this flight were used to generate a DTM. These results are compared to the ground truth data for the same area. The Impulse radar analysis is not treated here as the snow depth on the ridge was minimal due to the wind sweeping action of the strong surface winds.

Results

The bird altitude above the ridge for the evaluation flight line was approximately 15 metres. The EM footprint would therefore be approximately 15 metres as well. Figure 4 and 5 illustrate the ground truth surveyed sail and keel geometry for the area of the EM swath.

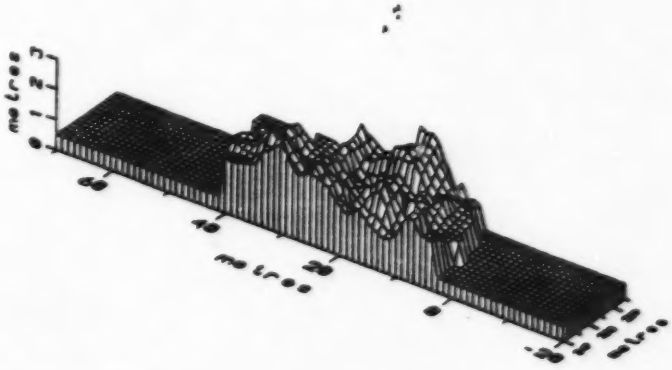


Figure 4 DTM of Sail Geometry for flight line 3

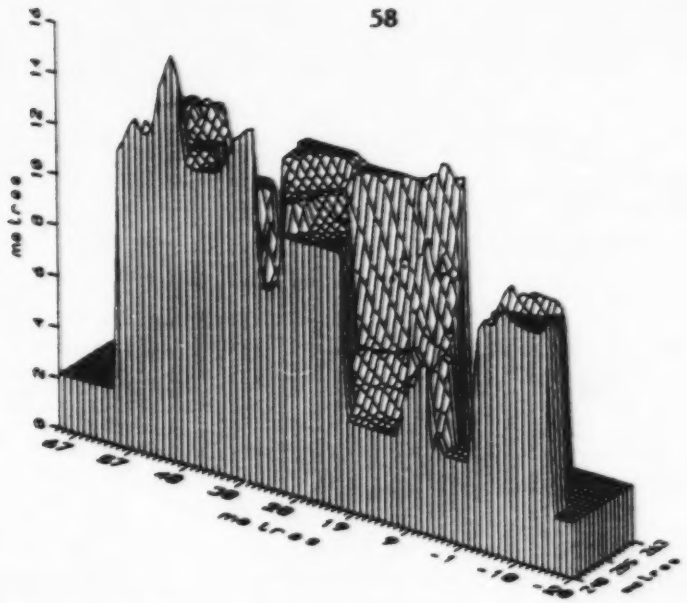


Figure 5 DTM of Keel Geometry for flight line 3

EM data was initially interpreted using a standard 1-D inversion algorithm as illustrated in Figure 6. From even a quick visual comparison it can be seen that the EM total ice thickness estimates obtained from this method of interpretation significantly underestimates the total ground truth results for the same area. The 1-D EM maximum total thickness of approximately 6 metres is two to three times less then the maximum thickness obtained from the combined top and bottom surveyed data. This first treatment of the data generally produces accurate results over level ice; however, rough ice topography requires a more sophisticated 2-D interpretation method.

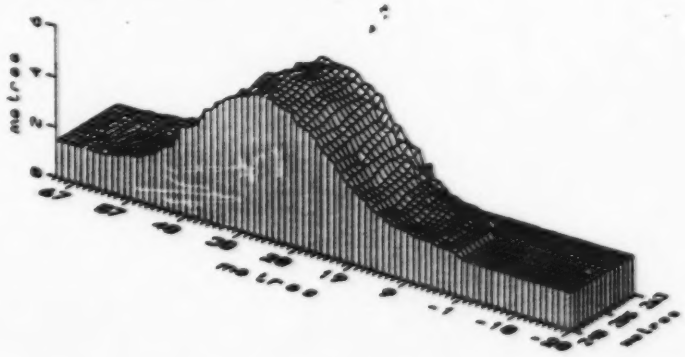


Figure 6 DTM of 1-D EM total thickness data interpretation for flight line 3

For the purposes of this paper, a 2-D co-axial interpretation nomogram (Liu and Becker,1990) was used to obtain geometry attributes of the ridge from the raw EM data. This nomogram compares the normalized anomaly amplitude, that is the EM anomaly amplitude as the system encounters the keel divided by the EM background response expressed as a percentage, to the normalized anomaly width which is the width anomaly at

one half of its maximum value divided by the bird altitude above the ice/water interface. This nomogram was constructed under the assumption that a typical keel shape approximates a Gaussian curve and that ice is essentially a perfect insulator and sea water an infinitely conductive medium.

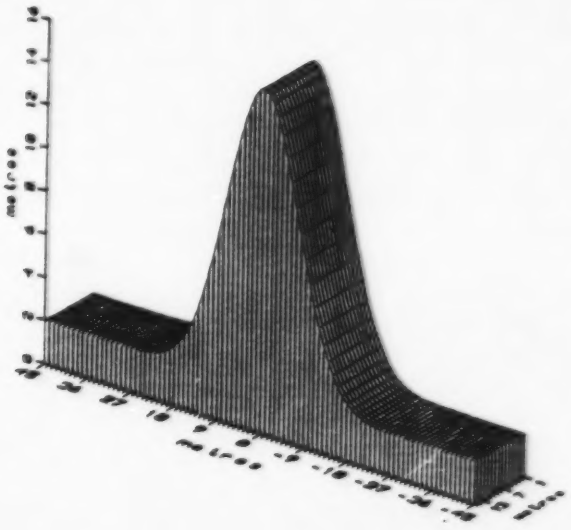


Figure 7 DTM of 2-D EM total thickness data interpretation for flight line 3
(based on a bird speed of 60 km/hr)

Preliminary estimates of the draft and width of the keel were 14 ± 3 m and 35 ± 4 m respectively. When compared to the underside DTM in Figure 5, the EM estimated draft of 16 metres approximates the ground truth findings very well. The EM keel width estimation is; however, only half the width of the ground truth keel width. In should be noted that this estimation of the keel width was based partially on a bird speed resolved from GPS results. A more thorough investigation of the bird speed produced a bird speed range of 59.5 - 87 km/hr. Visual estimates of bird speed from video records were approximately 78 km/hr. Calculations based on a bird speed of 87 km/hr produced a keel width of 52.5 ± 6 metres which is much closer to the submersible data obtained.
Comparison of extreme thickness and keel width is, however, a very coarse method to evaluate the EM performance.

The upward looking video of the TARS, although obscured somewhat by low light levels revealed an irregular keel surface with a variety of ice block orientations. The keel consisted of a complicated jumble of large ice blocks with some jutting vertically downwards. These features are far beyond the resolution of the airborne system. Since the EM is averaging over an approximate 15 metre footprint, a more useful comparison would be to calculate ice volumes. Calculations of volumes were made using Simpson's, Simpson's 3/8 and trapezoid rules. The 2-D EM volumes were calculated numerically and verified analytically. These calculated volumes are as follows:

Sail volume: 1318 cu metres
Keel volume 10316 cu metres
1-D EM volume 3206 cu metres
2-D EM volume 5411 cu metres (min) (60 km/hr)
2-D EM volume 7971 cu metres (max) (60 km/hr)
2-D EM volume 6766 cu metres (min) (87 km/hr)
2-D EM volume 10620 cu metres (max) (87 km/hr)

The keel volume obtained from the submersible surveys was 3.2 times that of the 1-D EM data interpretation. The 2-D approach, depending on the actual speed of the bird, ranged from 1.9 times that of the submersible data to an almost 1:1 volume fit.

Discussion

It would appear from this preliminary evaluation that the airborne remote sensing system has improved significantly over the previous efforts. The 1-D volume estimation significantly underestimated the total thickness as is expected for irregular ice topography. Ridge geometry strongly violates the 1-D assumption used for fast, automated interpretation of the EM sounding data. The 2-D estimation of the keel volumes reveals a promising approach to EM data interpretation. In order to assess the actual volume that the 2-D model estimates; however, in is necessary to have a more accurate method to obtain the flight speed of the bird. The system, although it appears to be measuring the overall volume of the ridge, still is quite limited in terms of feature resolution. It must also be noted that this evaluation is only based on one overflight and that further evaluation will be carried out on two more overflights of the same ridge at different locations. Given the nature of the irregularity of the keel surface, the task of remotely sensing the geometry of the keel is formidable. Further testing of the airborne system and supporting ground truth measurements over ridges of varying geometry and other irregular features, coupled with further development efforts to improve the interpretation software, are clearly indicated.

A possible reason for the EM's underestimation of the total ice volume of the ridge may be related to the structure of the ridge. Underwater video coverage revealed a keel block structure containing many voids. Generally, during the formation of pressure ridges, blocks are forced downwards and voids between blocks are filled with sea water. Initially the ridge is essentially a rubble field of unconsolidated blocks. Over time the rubble begins to refreeze, welding blocks together by the water contained within the voids(Timco et al,1987). This advancing consolidated/unconsolidated interface may be where the EM signal is reflected distinguishing the different conductivity values of consolidated ice and ice with water voids. This reflective interface may be further complicated by the concentration of brine contained within the voids. Large voids, cut off from the lower water body, would concentrate the brine content during consolidation. These large pockets of brine, much larger and more concentrated than those found at intercrystalline and platelet boundaries would have greater conductivity properties than the surrounding ice. These localized pockets could create significant secondary magnetic field anomalies and therefore complicate the interpretation of the received signal. It should be noted that the EM system was designed to minimize this effect by operating at the relatively low frequency of 2.5kHz. At lower

frequencies, attenuation of the EM signal by entrained water is reduced, pushing the principal reflective interface closer to the true keel boundaries.

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References

Holladay,J.S., Rossiter, J.R. and A. Kovacs, 1990. Airborne Measurement of Sea Ice Thickness using Electromagnetic Induction Sounding. Proc. 9th International Conf. Offshore Mechanics and Arctic Engineering, pp.309-315.

Kovacs, A., Morey, R.M. and G.F.N. Cox, 1987. Modelling the Electromagnetic Property Trends in Sea Ice, Part 1. Cold Regions Science and Technology, Vol 14, pp. 207-235.

Kovacs, A. and S.Holladay, 1989. Development of an Airborne Sea Ice Thickness Measurement System and Field Results. CRREL Report 89-19, pp.1-47

Kovacs, A. and S.Holladay, 1990. Sea-Ice Thickness Measurement using a small airborne Electromagnetic Sounding System. Geophysics, Vol.55, No. 10, pp.1327-1337.

Lintz, J. and D. Simonett, 1976. Remote Sensing of Environment. Addison-Wesley Publishing Company, Massachusetts.

Liu, G., and A. Becker, 1990. Two-Dimensional mapping of Sea Ice Keels with Airborne Electromagnetics. Geophysics, Vol.55, No.2, pp.239-248.

Nautronix Acoustic Tracking System ATS-S04 manual, 1989.

Rossiter, J.R. and L.A. Lalumiere, 1988. Evaluation of Sea Ice Thickness Sensors. Canpolar Project Number 1027 (for Transport Canada), pp. 1-58.

Shuchman, R.A. and R.G. Onstott, 1990. Remote Sensing of the Polar Oceans. Polar Oceanography Part A: Physical Science. Academic Press, New York.

Timco, G.W., Goodrich, L.E., Bowen, R.G. and J.C. Plunkett, 1987. Experiments on the Freezing of Ice Rubble. D.M.E./N.R.C. Technical Report 28288.